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Mine Power Distribution

Proceedings: Bureau of Mines Technology Transfer Seminar, Pittsburgh, Pa., March 19, 1975

UNITED STATES DEPARTMENT OF THE INTERIOR

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Compiled by Staff–Mining Research
Pittsburgh Mining and Safety Research Center, Pittsburgh, Pa.

UNITED STATES DEPARTMENT OF THE INTERIOR
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MINE POWER DISTRIBUTION

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ABSTRACT

The papers contained herein summarize results of various recent Bureau of Mines investigations in the area of mine power distribution systems. They are based on information from Bureau personnel, contractors and grantees, and Mining Enforcement and Safety Administration. Conclusions drawn from a series of parameter measurements on mine power systems, taken over a 3-year span, are presented. Personnel and equipment hazards due to faults on isolated, solidly grounded, and resistance grounded three-phase systems are discussed. Two papers cover dc applications of circuit breakers, including a novel protection scheme for trolley lines. The methods of suppressing induced arcing currents and voltages in a-c machines are evaluated. An evaluation program for ground monitors is described. Acceptance test procedures and the importance of various paparameters for trailing cable splice are covered. A number of techniques for locating faults in trailing cables are described.

INTRODUCTION[1]

Electric power is an essential component in the operation of an underground coal mine; the importance of the electrical system in a mine and the potential for hazardous conditions is exemplified by the quantity of statutory and promulgated rules and regulations of the Coal Mine Health and Safety Act of 1969, Public Law 91-173, that pertain to electrical items. The Bureau of Mines, under its coal mine health and safety research program, has been investigating coal mine electrical problems and developing solutions for them.

The Bureau program is generally divided into three areas: (1) Analysis of electrical systems, (2) evaluation of existing hardware, and (3) the development of new hardware and systems. The papers presented at this seminar and contained in these proceedings covers work in each of these areas.

The Bureau program is implemented through in-house and contract research as well as through joint evaluations with technical experts in the Mining Enforcement and Safety Administration (MESA). The papers of this seminar

[1]John N. Murphy, research supervisor, Pittsburgh Mining and Safety Research Center, Pittsburgh, Pa.

reflect the work of the Bureau specialists, the Bureau contractors, and MESA personnel. Most of the projects described have involved extensive fieldwork that has been possible only through the cooperation and assistance provided by the coal mine operators and their personnel to whom we are indebted.

The Bureau research program that has produced the results described herein is a continuing effort. The progress presented is believed to be of use to the mining industry, but additional accomplishments are needed before total success can be claimed. The input of concerned individuals and organizations including management, labor, suppliers, and inspectors is encouraged. The Bureau's mine electrical program is administered by George J. Conroy, Pittsburgh Mining and Safety Research Center, and to him the credit is due for the success of the program and of this seminar.

UTILIZATION AND EFFICIENCY IN UNDERGROUND COAL MINE ELECTRICAL SYSTEMS

by

Lloyd A. Morley[1]

ABSTRACT

To reduce safety and production problems, it is essential that the electrical operating characteristics of coal mining equipment and their electrical subsystems be clearly understood. The Bureau of Mines and the Pennsylvania State University have developed techniques to monitor and analyze several of the critical parameters.

A unique system for measuring traction locomotive consumption at the machine has been assembled and utilized. Conclusions from 27 continuous miners show that voltage levels are directly tied to machine efficiency.

The Bureau of Mines and Pennsylvania State University, along with West Virginia University, are currently monitoring and accessing mine power transients. Results exhibit that voltage transients of three to five times the line-to-line value are common on underground distribution systems.

INTRODUCTION

The electrical power system is the backbone of present underground coal mines; it drives practically every piece of equipment that is used for production. Consequently, the subject of utilization and efficiency is very important to mine operators. To reduce safety and production problems, it is essential that the electrical operating characteristics of coal mining equipment and their electrical subsystems be clearly understood. For the past 4 years, Penn State's Department of Mineral Engineering, through funding by the Bureau of Mines Coal Mine Health and Safety Program, has been monitoring and analyzing several of the critical parameters tied to this equipment. The reason has been to find answers or sources to the answers for certain mine electrical power problems confronting today's mine operator.

This presentation covers just four areas of Penn State's work:

1. Continuous miner operation,
2. High side distribution (tied to item one),
3. Traction locomotive characteristics, and
4. Mine power system transients.

The first three topics and their related problems are not new to the industry, but the last happens to be a relatively recent addition to mine operator's worries.

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[1]Associate professor of Mining Engineering and director of Mine Power System Research, Department of Mineral Engineering, The Pennsylvania State University, University Park, Pa.

The main goal of the research is to increase mine electrical safety by gaining a more adequate knowledge of the electrical system. However, by taking note of electrical safety problem areas in mine, production can be substantially enhanced.

PRODUCTION LOSSES

Considering everything for which mine operators pay (labor, equipment, royalties, maintenance, and so forth), even with the recent substantial increases, the actual cost for electrical power seems very small. Consequently, why should we worry if our equipment is not running efficiently on an electrical standpoint? During one of several measurement trips, the mine superintendent asked exactly this question of the research group. His company's electrical engineers had selected one section that typically represented his mine and, further, would provide the necessary electrical data the project needed.

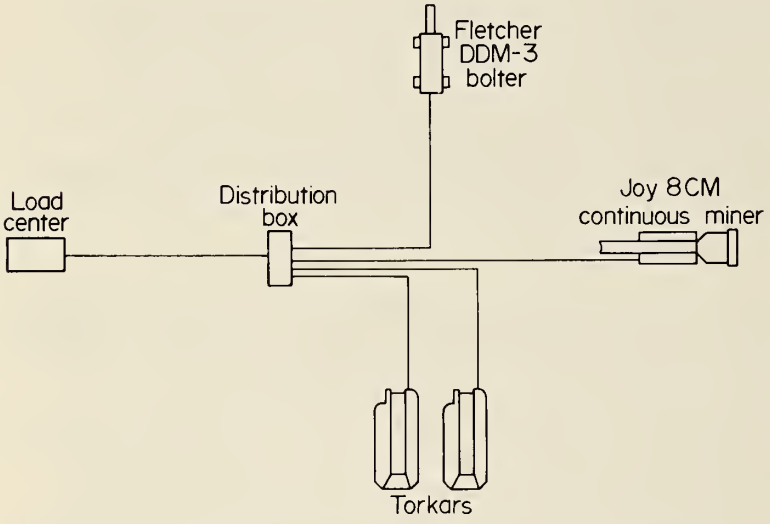


FIGURE 1. - Developing continuous mining section.

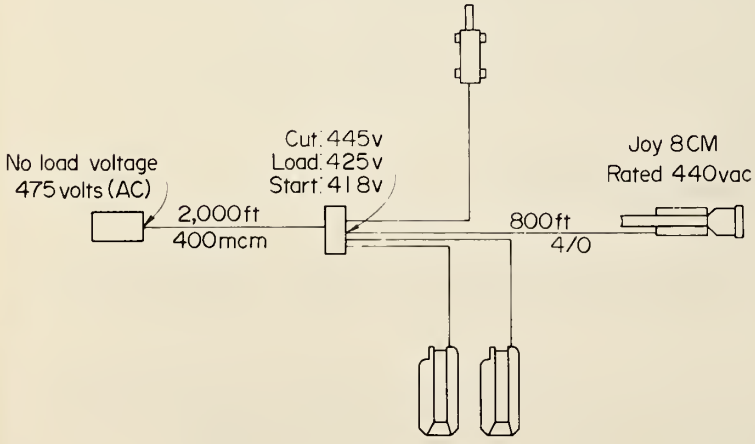


FIGURE 2. - Typical section voltages.

This developing continuous mining section is illustrated in figure 1. During actual measurement, it was found that the continuous miner was having several problems. Basically, when the cutting motors were started or at high operating periods, the machine's contactors easily dropped out. Other equipment, specifically one shuttle car, were also experiencing circuit breaker problems. Maintenance personnel suspected one cutter drive motor as the culprit for the miner, and a bad trailing cable was supposedly creating the shuttle car's problems. They spent two shifts replacing the motor. Yet after the motor replacement, the operation of the miner was exactly the same.

While investigating the section recordings at Penn State, the first thing noticed was the voltage levels on all equipment appeared extremely low (fig. 2). Typical voltages at the distribution box were as follows:

1. 475 V ac, no load;
2. 445 V ac, miner cutting;
3. 425 V ac, miner under high load; and
4. 418 V ac, cutting motor starting.

An idea of how dynamic the voltage fluctuations were during miner starting is shown in figure 3. Taking into account the voltage drop across the miner's 4/0, 800-foot trailing cable, the voltages at the machine for the last three conditions mentioned previously were 397, 349, and 337 V ac, respectively. All are at or below the minus 10 percent voltage limit for 440-V ac induction motors. The main conclusions that can be made are (1) there was too much feeder and trailing cable, and (2) voltage taps at the transformer secondary were set too low.

Nevertheless, here was a mine section where actual power costs were probably low but production losses, obviously a result of poor electrical operation, were high. In other words, the mine superintendent was paying more for the electricity than he actually believed. The company's electrical engineers were amazed to hear about the low voltage condition. Upon the investigator's recommendation and the company's concurrence, the load center's secondary connection was set at a higher tap; the feeder cable and the miner's trailing cable were shortened. Afterwards, the contactor problem disappeared.

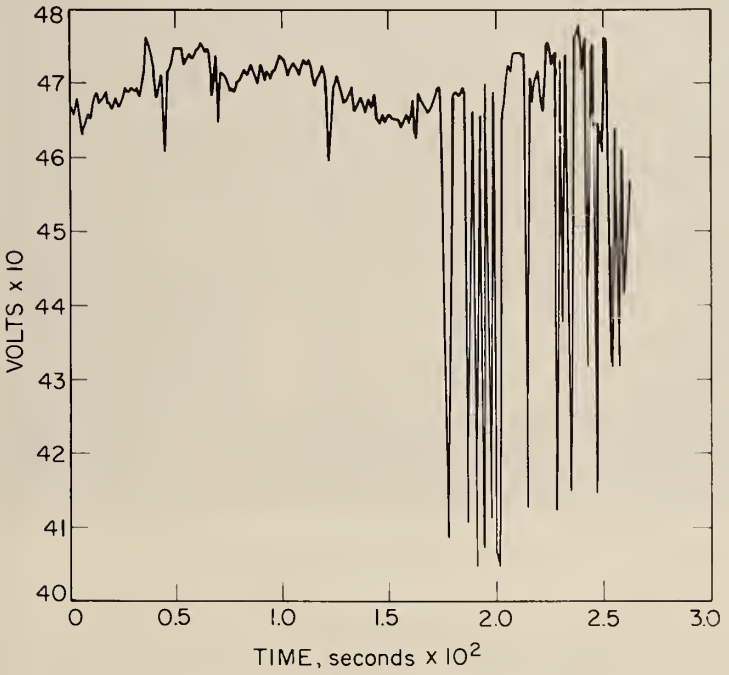


FIGURE 3. - Voltage fluctuations at the distribution box during miner starting.

This particular instance is only one of the problems found in all of the measurements taken, but low voltage operation is the most repetitive. Before looking directly at some addition problems, let's briefly cover how Penn State's research group measures electrical parameters underground.

MEASUREMENT TECHNIQUES

At the beginning of this work, no instrument package was directly available commercially that was capable of recording complete dynamic power data in the underground coal mine environment. Consequently, apparatus essential to the research had to be constructed. Criteria for building included safety, precision, and reliability

plus minimum mine operator interference and no production interruption. Load centers, distribution boxes, and switchgear were selected as the best measurement locations using identical cable couplers in line with the trailing or feeder cable. Figure 4 schematically illustrates how the equipment is installed in the power system. Figures 5 through 7 show some typical setups and components.

With these instruments, all electrical parameters are measured on a simultaneous, continuous basis. Therefore, the procured data can be cross-checked for recording precision, instrument reliability, and reconstruction of any lost information.

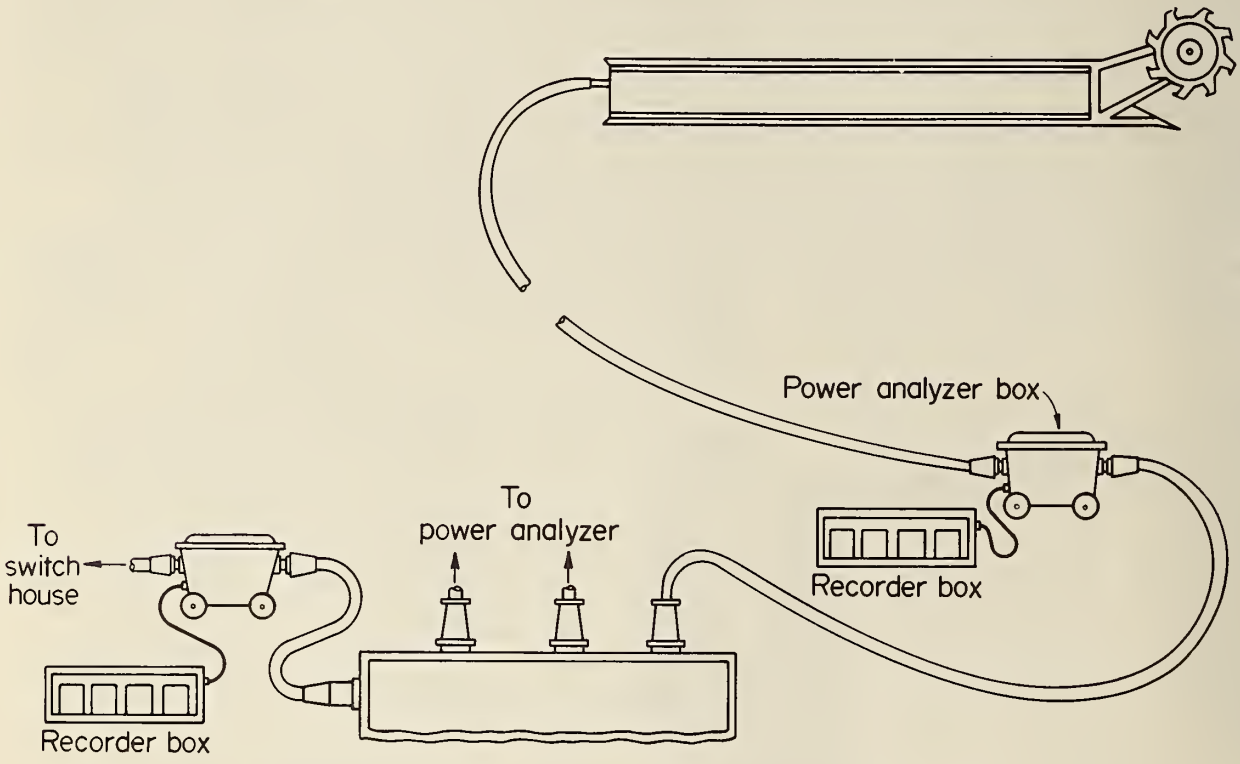


FIGURE 4. - Typical instrument connections.

FIGURE 5. - Underground high-voltage installation showing a transducer cart.

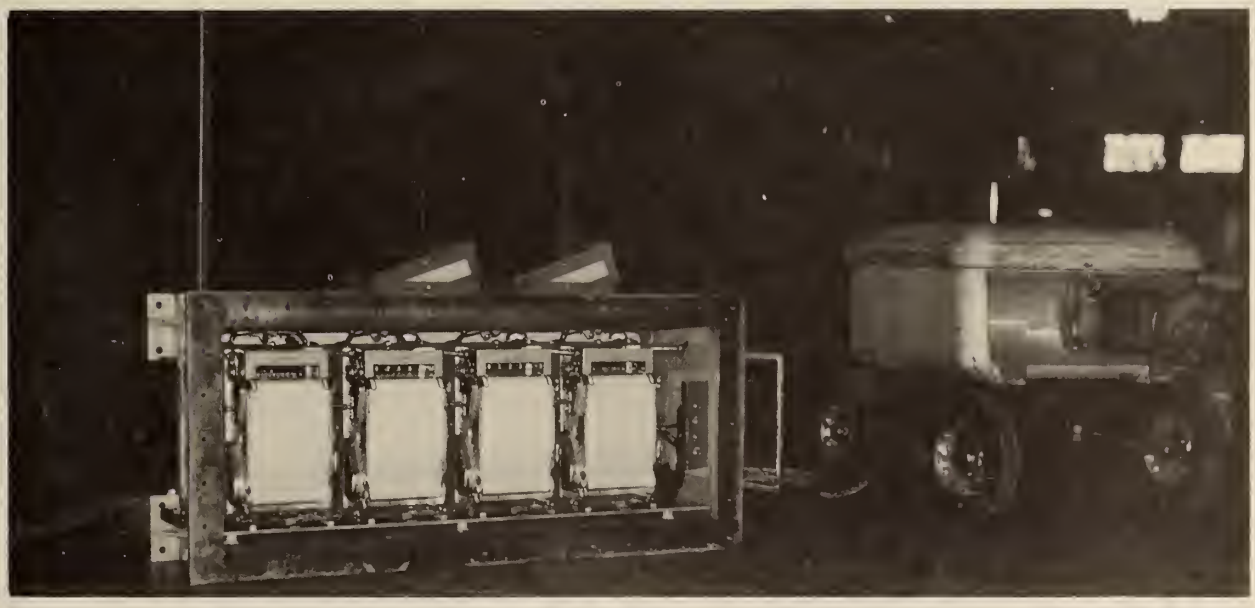


FIGURE 6. - Low-voltage measurement system with strip chart recorders.

The basic instrument package is relatively simple and set up so the mine operator can easily construct his equipment then utilize it to check the operation of his own electrical system. Examples of how it can be used include finding precise values for load center power factor correction capacitors or to check belt drive motor loading. Perhaps, a mine operator on this last point could extend his belts per unit drive.

FIGURE 7. - Digital recording system.

CONTINUOUS MINER OPERATION

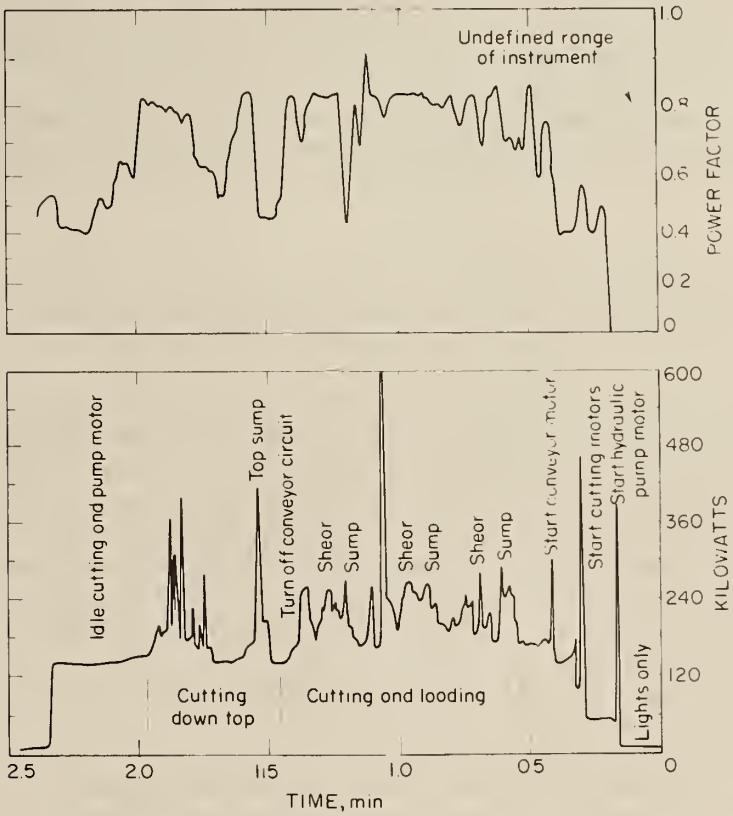
Of all electrical equipment used in U.S. underground coal mines, the continuous miner relates to perhaps the majority of electrical problems. It is the heart of present underground coal mining systems both on production and electrical standpoints. The power parameters of 27 voltages are 440, 550, and 950 V ac, and the total rated motor powers range from 100 to 535 hp. A listing of manufacturers and model numbers is available in table 1. These machines are operating in the Appalachian coalfied. Productions range from 50 to 770 raw tons per shift.

TABLE 1. - Continuous miners measured

Number	Type	Number	Type
1	Alpine FGA	1	Lee Norse II
1	Jeffrey 76AM	7	Lee Norse CM26H
3	Joy 8CM	1	Lee Norse CM28E
1	Joy 9CM	2	Lee Norse CM28H
6	Joy 10CM	1	Lee Norse CM35Y
1	Joy 12CM	1	Lee Norse HH455
1	Joy CU43-2H		

The following statements relate to ac continuous miners designed for high production coal winning, thus eliminating the Alpine[2] and Jeffrey miners. One term, load factor, used in the discussion needs to be explained. Machine load factor can be defined as the ratio of power the machine is using to the power at which the motors are rated. Alternating current continuous miners use squirrel-cage induction motors, and for these the rated power is set by the manufacturer for either one motor or a combination. Because no ratings exist between coal mining equipment manufacturers, motors are normally rated by National Electrical Manufacturers Association guidelines but sometimes can be designed on a job-shop basis. Still torque and power are the only ratings available by which to judge motor utilization. Because horsepower is directly proportional to the product of motor speed and torque, the power rating can be employed to determine three phase motor performance. The load factor can be used not only to judge effective operation of a particular machine but to compare different continuous miners regardless of the rated power.

At low load conditions, motor efficiency and power factor drop off rapidly. Furthermore, the motor functions on the steep portion of the power factor curve, which means a small load variation will cause a relatively large motor current fluctuation. This can produce detrimental current peaks and stresses in trailing and feeder cables, particularly in marginal size conductors. Poor power factor operation additionally means either correction capacitors or heavy utility company penalties.



Cutting ond loading operotional curve for o Joy 8CM(10CM) continuous miner

FIGURE 8. - Typical set of cutting and loading electrical parameters.

Figure 8 shows a typical set of electrical curves for a miner while it was cutting and loading. Average load factors have been found for each measured machine using curves similar to these shown. Mainly because cutting power consumption is the most demanding, the study has been focused on this operational cycle. Several interesting findings have occurred from analysis comparing all the continuous miners.

[2]Reference to specific equipment does not imply endorsement by the Bureau of Mines.

Load Factors and Machine Horsepower

Typical average cutting load factors range from 0.26 to 1.17 and average 0.48. When all hydraulic, mechanical, and electrical machine components are employed, a 0.60 load factor can be considered satisfactory. Therefore, the implication is that the majority are being used inefficiently. Because of the numerous factors involved, making conclusions about machine efficiency and utilization by just the load factors alone can be misleading. However, an important finding here is that 0.48 is much less than the preceding assumed design level of 0.85 popularly used by the industry.

Generally, low to moderately powered machines have higher load factors, some of which are considered totally adequate. During field measurements, close attention was paid to the machine operator's performance by the individual taking time studies. In almost every case, the operator was pushing his machine as much as possible during cutting (actually, sumping) because traction approached full slip. From adequate employment, some of these machines can be termed overpowered, for example, a high-powered machine cutting very friable coal.

In general, the majority of the measured machines' cutting motors have too high horsepower. One company, working with this research group and realizing the situation, is replacing its 175-hp cutting motors with 135-hp motors (mainly during overhauls). With the smaller motors, load factors and power factors have improved. More importantly, not one of the converted machines is overpowered on an average basis. However, even with this example of improvement, firm evidence exists that subsystem voltage levels and cable lengths are the main restraining factors in effective continuous miner utilization.

Trailing cables.-- On low-voltage systems, even with good continuous miner operation, the 4/0 (or sometimes 2/0 and 1/0) trailing cable is the "weak link" of the subsystem. It is apparent that weight and lack of flexibility restrict the use of larger conductors than 4/0. This size trailing cable is normally rated at 220 A at 40° C, and almost all continuous miners measured using 4/0 trailing cable averaged well over the rated level during cutting (for instance, one 525-hp machine averaged 480 amperes). The same was true for the smaller trailing cables when compared with their rated current. Such current on a continuous basis can cause accelerated cable deterioration from overheating. Furthermore, when a high-horsepower machine (say, 500 hp or more) is used on a low-voltage system, its demand for large current can create large trailing cable voltage drops and a machine voltage condition that not only hampers operation but reduces the safety levels of the system on which the machine operates (for example, substantially reduced motor torque capabilities, poor power factor, and so on).

Recommendations.--On almost a one-for-one machine comparison, good voltage conditions at the machine result in good motor load factors and, therefore, good power factors. To obtain the favorable operation requires not only "good voltage" but a strong distribution system. This is a help in purchasing new machines, and it is strongly recommended that mine operators

consider 950-V ac face utilization for their continuous miners. The higher face voltages can substantially reduce trailing cable current. However, what about the present low-voltage systems? Here are a few suggestions. Use 4/0 trailing cables and keep them short, not greater than 500 feet, even though you could perhaps use a 2/0 conductor size. Maintain your low side (load center) taps as high as possible. On 440-V ac systems, this means setting them at 505 V ac (14.8 pct above the rated motor level). Considering trailing cable losses and normal insulation dielectric strengths, the high no-load voltages should present no problems but should aid in general continuous miner operation. Most low-voltage systems that have been judged as having good miner performance strictly adhere to these two suggestions.

Distribution Voltages.--The recommendation for a strong subsystem also applies to distribution. When high side voltage regulation is bad, normally poor machine load factors occur. The situation is most evident on 4,160-Vac distribution systems that have been extended beyond their limits.

During analysis, one continuous miner that was measured was found to have adequate voltage conditions at the machine but the poorest load factors of all. The nominal distribution voltage to the load center of this machine was 4,160 V ac. The mine operator, suspecting voltage problems, asked to have the high side parameters measured simulataneously with the regular low side work. The high side voltage regulation, during continuous miner starting, was found to be about 6.0 pct; high continuous miner shear loading accounted for 4.5 to 5.0 pct. High voltage regulation should be maintained under 2.0 pct, and the observed values are the probable reason for that machine's poor load factors. The measurement conclusions have resulted in the mine operator installing a new borehole at 7,200 V ac.

MACHINE OPERATION

In researching the previous work, additional help has been uncovered for the mine operator.

Direction of Cut.--It has been universally assumed but never proved in the industry that cutting with the major cleat direction requires more power than against the cleats. Cutting aginst the cleats enables the coal to spall from the face because of the natural weakness planes. Measurements on three continuous miners bear out this contention. Working in heavily defined cleat seams, they have power changes of 20 to 30 pct depending on direction. Other measurements have shown that cutting 45° to the cleat direction also requires less power than cutting against the cleats.

Use of this information can lower the mine's overall power consumption. For example, if room-and-pillar entries are laid out perpendicular to the major cleat direction, the easiest cutting will be in the entries, the primary production direction. Hence, a predictable lower power requirement would occur. However, the magnitude of the advantage gained is definitely dependent on the cleat structure.

Sump-Shear Loads.--On machines where full shear can be developed (for example, in high coal), shear power consumption is generally much higher than during sumping. For these conditions, the present indication is that maximum continuous miner loading occurs during shear. Furthermore, optimum loading during both operations happens when the miner is sumped to the maximum cutter diameter.

Good production techniques usually call for sumping to the maximum cutter diameter. The measurements taken indicate that good electrical operation also requires this. Poor machine electrical loading along with poor power factor almost always occurs when a machine only sumps lightly (to a shallow depth) rather than shears.

TRACTION LOCOMOTIVES

The investigation of traction locomotives and the next subject are continuing projects for the Bureau. Although not yet complete, the projects are included not only for the importance to the industry but to illustrate some of the work this research group is presently performing. The main objective behind the electrical study of locomotives is, as previously stated, to gain an adequate knowledge of mine power systems.

The most logical place to measure the characteristics of a mine locomotive is at the machine itself, but to monitor at this location creates several technical problems. However, working very closely with company personnel of a large southwestern Pennsylvania coal mining division, the majority of the questions are resolved. The decision was made to place all heavy instruments in a weighted mine car directly behind the locomotive. The instruments include (1) a digital tape recording system to eliminate strip recorders and their inherent problems, and (2) a battery/inverter to supply 110 Vac. The current shunt and necessary dc recording transducers are mounted directly on the locomotive. The complete system is schematically illustrated in figure 9 with an installation shown in figure 10.

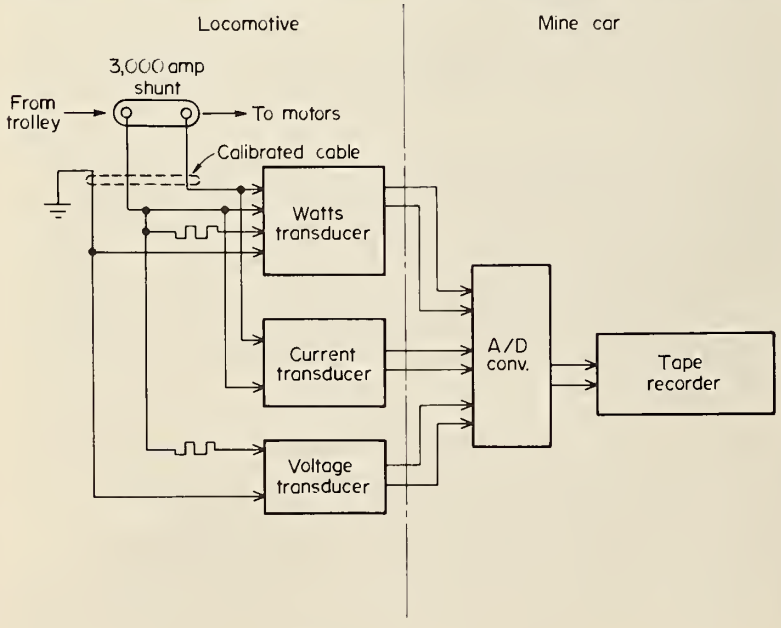


FIGURE 9. - Locomotive instrument schematic.

A 27-ton locomotive has already been measured with the system. Its duty is mainline underground haulage, but the reason to measure this specific machine goes beyond those already stated. The company has been experiencing several motor armature failures (47 in 1973),

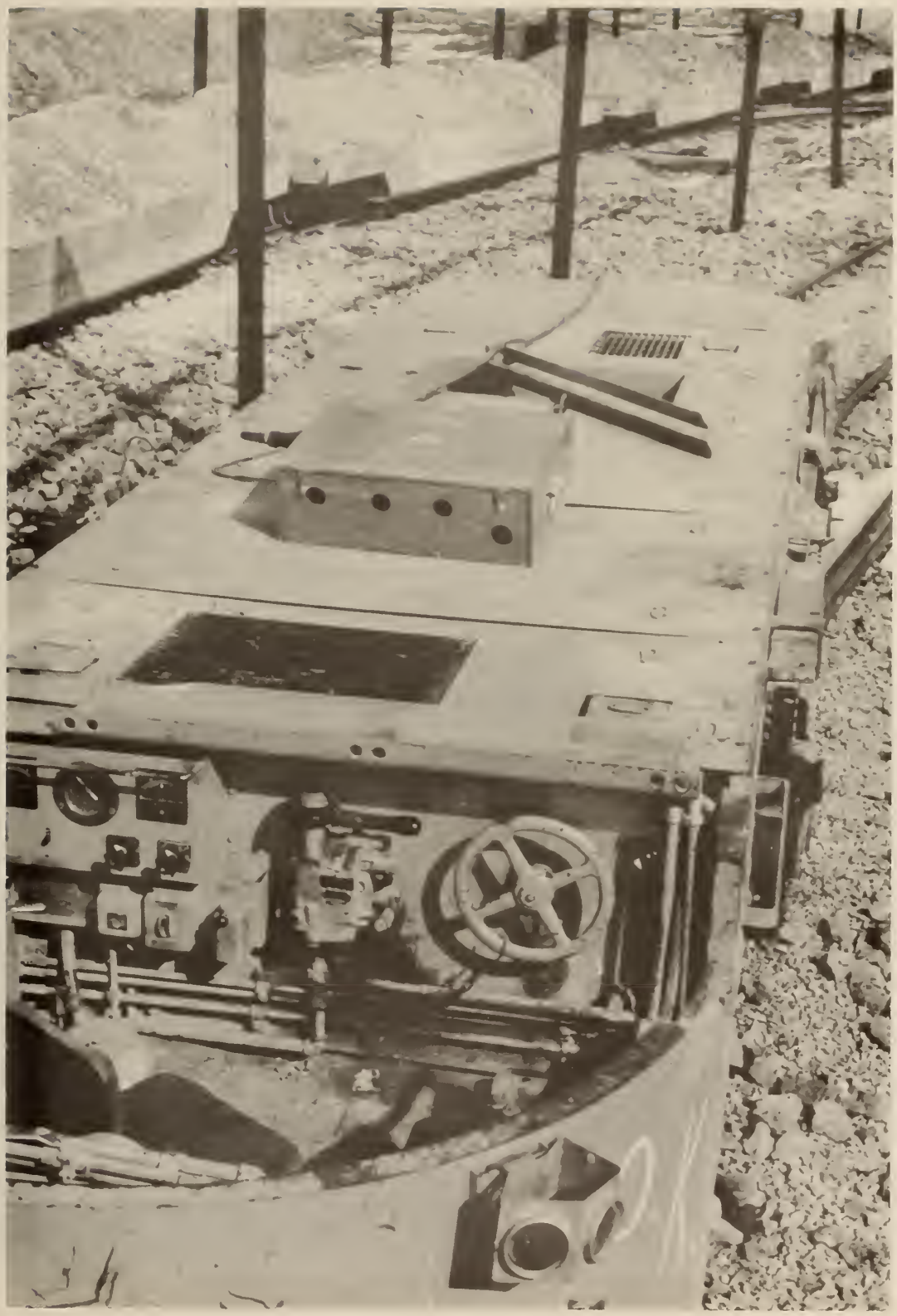


FIGURE 10. - Locomotive installation.

and their personnel contacted us directly to enlist our help. Subsequent inspection of failed armatures indicated that the problem was overcurrent (heavily pitted and charred commutators).

Even with some technical problems and subsequent data loss, the measurement system worked. Data obtained substantiates the suspected over-current problem. By correlation of time studies taken directly on the locomotive, the recordings show that a severe continuous stress on the motors was occurring every time the locomotive proceeded through a particular curve (fig. 11). This is located on a steep grade near the end of the loaded trip out.

Subsequently, the company has reduced the locomotive's trailing load. With the reduction, the machine has shown a tremendous operational improvement. The instrument technical problems have been resolved, and measurements are proceeding under varying mine conditions.

The direction to the solution of this problem was low voltages. However, differing from the previous section covering ac equipment, dc series wound motors are not hurt by low voltage although their associated control equipment might not function properly. Popular knowledge incorrectly believes that all motors overheat under these conditions. The soundness of this specific trolley distribution system (good maintenance, cross bonding, 1.0 Mcm negative and positive feeders, properly spaced rectifiers) indicated directly that the motors experienced overcurrent.

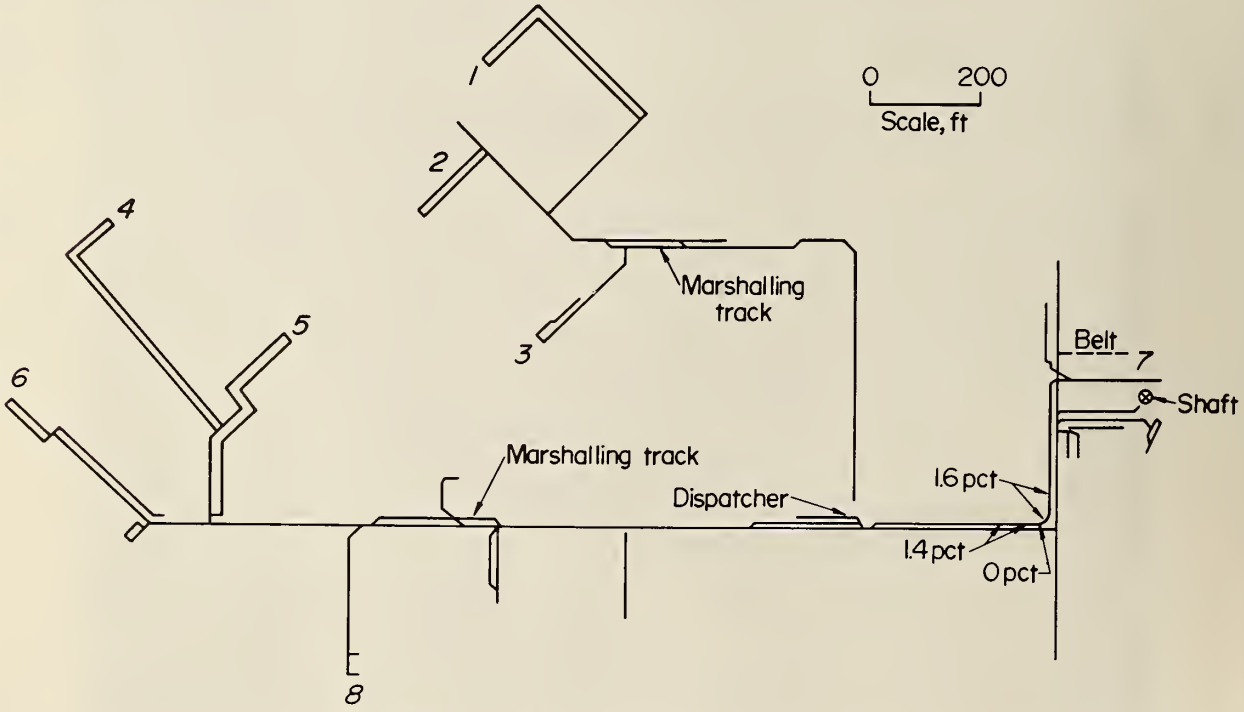


FIGURE 11. - Track layout.

TRANSIENT ANALYSIS

Transients are results of sudden changes that take place in power systems. They can occur within the underground electrical complex or can be carried in the mine from an occurrence in the utility company's system. Transients are of short duration. However, it is during these short periods that the greatest electrical stresses occur, mainly due to excessive currents or voltages. In extreme cases, system parts are damaged.

Problems firmly believed to directly result from these phenomena became apparent to the coal mining industry with the introduction underground of (1) 12.47 kV distribution, (2) vacuum circuit breakers, and (3) sensitive solid-state electronics apparatus and equipment controls.

This research is a joint effort among the Federal Bureau of Mines, the Mining Enforcement and Safety Administration, West Virginia University's Electrical Engineering Department, and Penn State's Mineral Engineering Department.

A system has been assembled, field tested, and is now being used. It consists of several electronic instruments that sample, monitor, digitize, and then record these occurrences. Figure 12 shows the instruments installed at a mine load center on a recent measurement trip.

FIGURE 12. - Transient recorder installation.

Although field studies are now just providing data, initial observations on high voltage distributions indicate the following:

1. Transients of five times the line-to-line voltage are common on 7,200-V and 12.47-kV systems.

2. Some peaks have gone to seven times the nominal peak voltage level (on one 12.47-kV system, a series of 93-kV transients were observed).

3. Durations are commonly in the microsecond range but can approach millisecond times.

Indications now are that the majority of current transients are coming in from the utility company, but several are being generated within the mine. Figures 13-14 illustrate actual current transients observed while a continuous miner was starting.

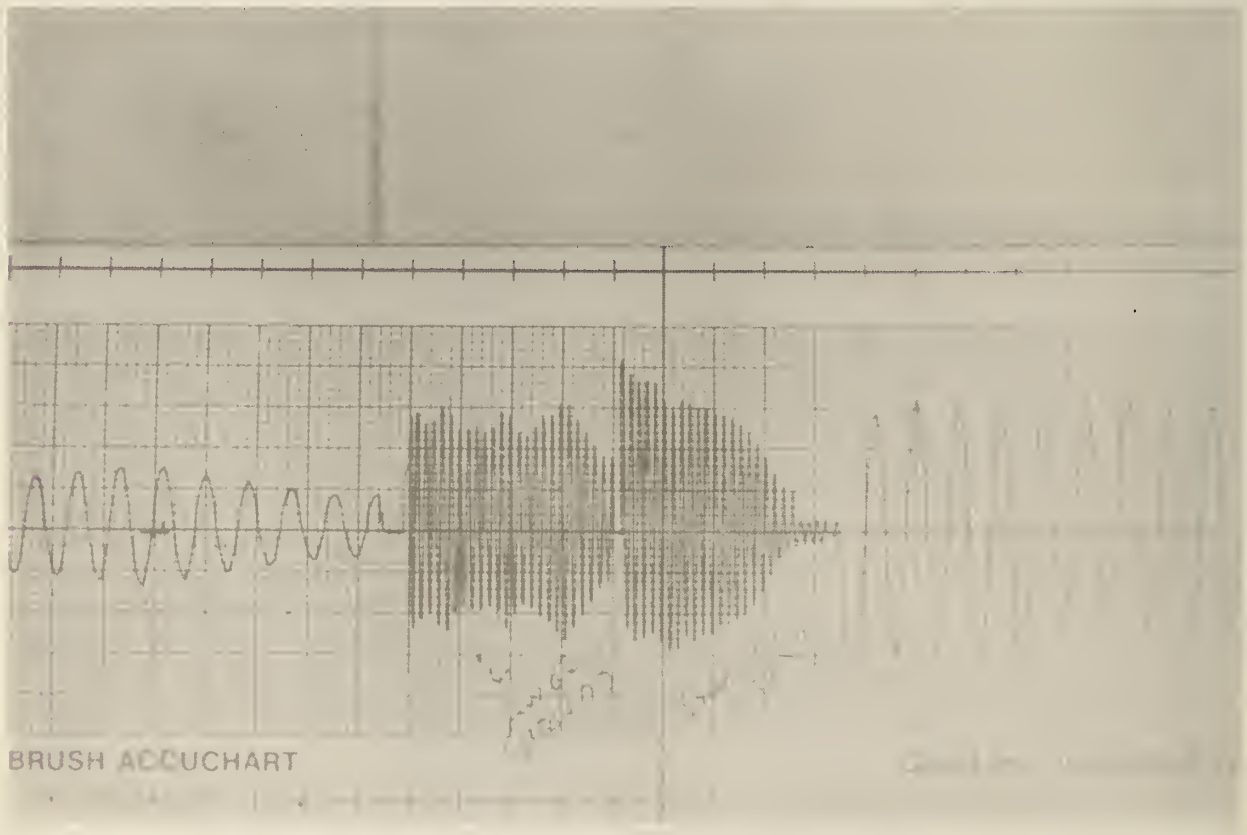


FIGURE 13. - Motor starting current transient.

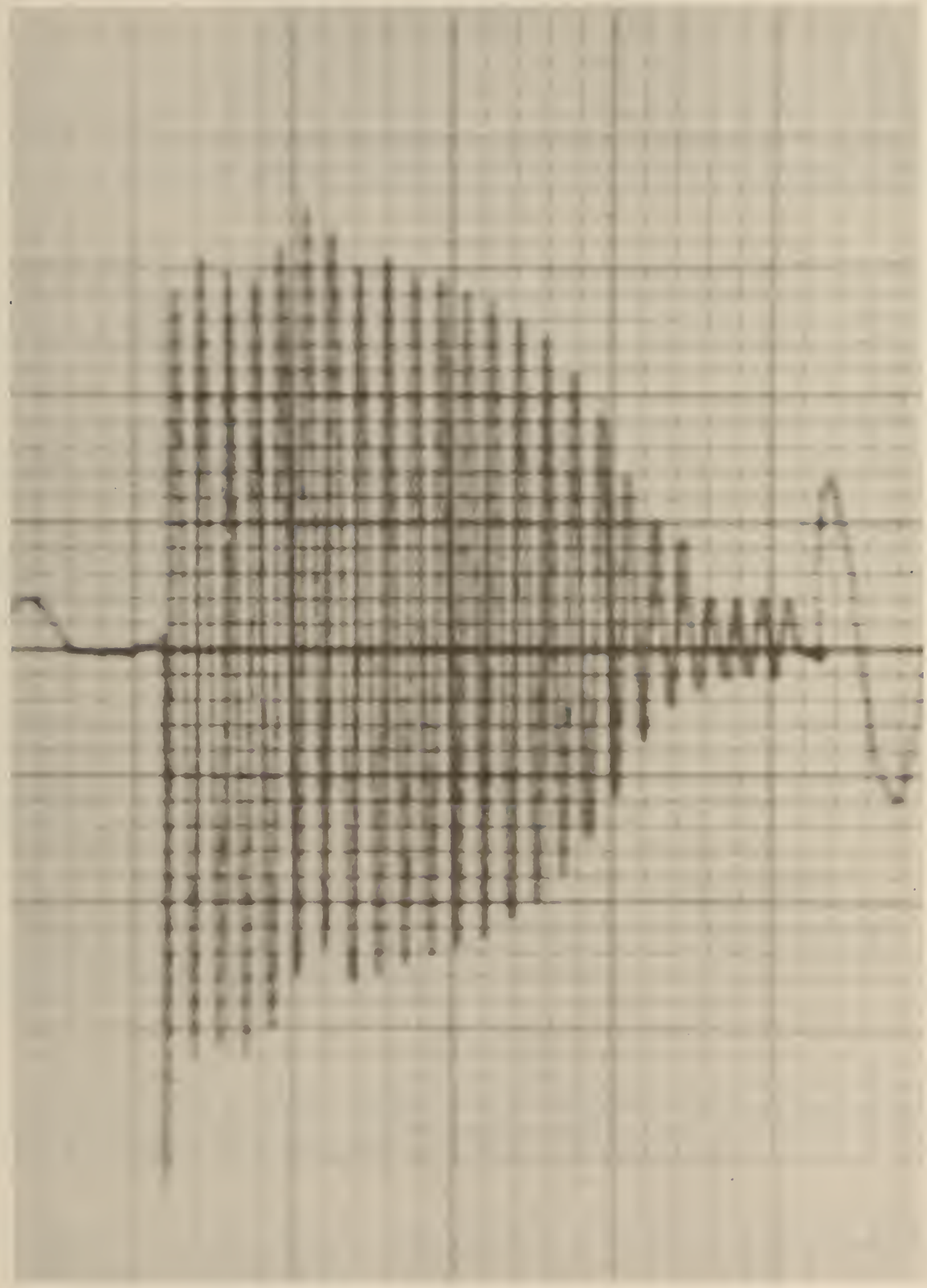


FIGURE 14. - Cutting motor starting current transient.

CONCLUSIONS

This main goal of this presentation has been to bring to industry the techniques and vital information that are a result of Penn State's research. The last 4 years of work has now made available to the coal mining industry (1) methods of measurement, (2) a large amount of background data for designing and planning mine electrical systems, and (3) several solutions to specific problems.

THE IMPORTANCE OF GROUNDING SYSTEMS IN THE PROTECTION OF PERSONNEL AND EQUIPMENT

by

Louis D. Dornetto[1]

ABSTRACT

The effects of electric shocks on man are an important factor in the design of power systems and protective devices. The current levels just below let-go and just prior to the onset of ventricular fibrillation must be known and taken into consideration in the design of power systems and protective devices.

Isolated (ungrounded) electrical distribution systems are compared with resistance and solidly grounded systems. The advantages and disadvantages of each are discussed and recommendations are made.

Transients on coal mine power systems are a problem that, until recently, have been ignored. Transient voltage levels that can be expected on both the high and low side of the load center and the effects of transients on electronic equipment and personnel are covered.

INTRODUCTION

The protection of mining personnel and equipment from deadly and damaging current and voltage levels can only be accomplished with a thorough understanding of what current levels are dangerous, what type of power system offers the best protection, and what degree of transient protection must be built into equipment. This paper describes each of these areas and makes recommendations for improvement.

THRESHOLD LIMITS OF THE HUMAN BODY TO ELECTRIC CURRENT

The extent to which the human body can withstand electric currents depends upon the frequency, magnitude, and duration of the current flowing through the vital areas of the body.

Frequency

The human body seems to be most susceptible to currents at the power frequencies of 50 or 60 Hz. The body can tolerate slightly higher current at 25 Hz and perhaps even five times as much on direct current.

[1]Electrical engineer, Industrial Hazards and Communications, Pittsburgh Mining and Safety Research Center, Bureau of Mines, U.S. Department of the Interior, Pittsburgh, Pa.

Magnitude

The following effects of varying the magnitude of the current applied to the body will be discussed:

1. Let-go current.
2. Paralysis.
3. Ventricular fibrillation.
4. Cardiac arrest.
5. Tissue destruction.

Let-Go Current

Let-go current is the maximum current that man can tolerate and still be able to release or let-go his grasp of an energized conductor by using the muscles directly stimulated by that current.

The let-go 60-Hz currents for men and women are approximately 9.0 mA (milliamperes) and 6.0 mA, respectively. Reasonably safe let-go dc currents for men and women are 62 mA and 41 mA, respectively.

Paralysis

The magnitude of the current just a little less than the let-go current is considered to be the maximum safe current because breathing becomes difficult or impossible due to paralysis of the breathing muscles at higher values of current.

Therefore, the design of a power system should be such that a man will not be subjected to more than 9.0 mA ac or 60 mA dc for a length of time that would result in death from asphyxiation.

Ventricular Fibrillation

Ventricular fibrillation is a condition in which the heart beats wildly out of control. The rhythmic pumping action ceases and death follows rapidly if the condition continues. This condition is not self-correcting after the current flow is cut off. Special equipment and medical skill are usually required to save the victim. Whether or not fibrillation occurs depends upon the magnitude and duration of current flow and the body weight of the individual involved.

From tests on animals, the relationship between the current and the time required to produce fibrillation in humans is an I^2t relationship. In other words $I^2t = K$. K is a constant. The value of K selected will not cause fibrillation in 99.5 pct of the humans subjected to that value of current. The value of K was also selected on the basis of a man weighing not less than 110 pounds, and for a duration of current flow between 8.0 msec and 5.0 sec. Using these criteria, K = 116. This resulted in the following formula:

$$I = \frac{116}{(t)^{1/2}},$$

in which I = total circuit current, in milliamperes,

and t = time, in seconds.

For example, when t = 0.008, I = 1,296.919 mA; when t = 5.0, I = 51.88 mA. These are the currents just below the value required to produce fibrillation in 0.008 and 5.0 sec.

The I^2t characteristic suggests a basis for the design of protective devices to minimize shock hazards, a basis of protection that has been used in some foreign coal mines. However, the most important consideration should be the 9 mA let-go current limitation since currents above this value may cause death by paralysis and asphyxiation.

Cardiac Arrest

There is evidence that current magnitudes considerably in excess of the values required to produce fibrillation may cause cardiac arrest. Cardiac arrest means that the heart stops beating for the duration of current flow. The heart usually starts again when the current stops flowing, provided that the current has not been on long. Since the heart usually starts again, cardiac arrest is thought to be less lethal than fibrillation, which is not self-correcting.

Tissue Destruction

The destruction of tissues results from shocks of high current magnitudes. Whether or not this is crippling or fatal depends on the tissues destroyed and the amount of irreversible damage.

Duration

The duration of current flow through the body is of major significance. A current of 10 mA may not be great enough to produce fibrillation; however, if breathing is interrupted for a sufficient period of time, it may cause asphyxiation.

In the design of power systems, it is, therefore, important to keep in mind the 9.0-mA limit for let-go currents and the I^2t relationships for protection devices.

ISOLATED, RESISTANCE, AND SOLIDLY GROUNDED SYSTEMS

Isolated System

An isolated (ungrounded) system is one without an intentional connection to ground except through potential indicating or measuring devices or through surge protective devices. Although called isolated, this type of system is, in reality, coupled to ground through the distributed capacitance of its phase windings and conductors (figs. 1-2).

A grounded system is one in which at least one conductor or point is intentionally grounded, either solidly or through a current-limiting device.

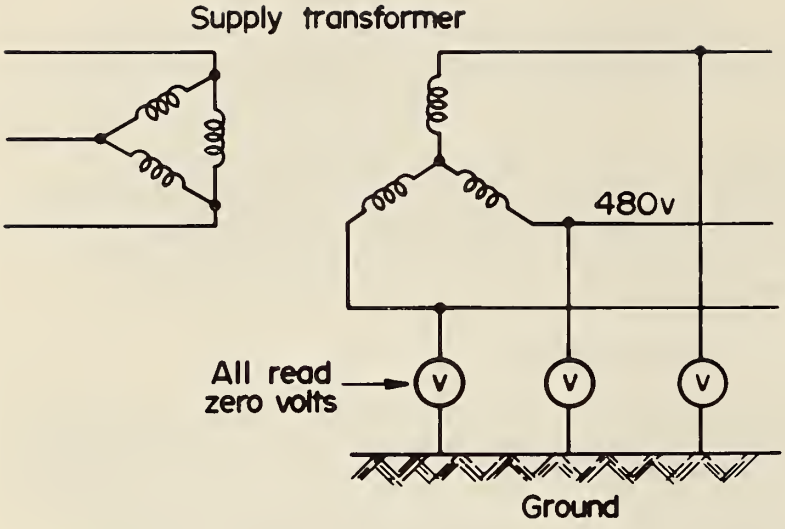


FIGURE 1. - Idealized ungrounded system (no distributed capacitance).

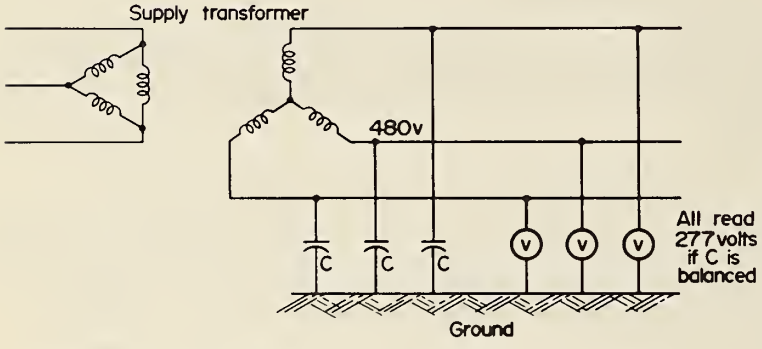


FIGURE 2. - Actual ungrounded system (with distributed capacitance).

Low Resistance Grounded Systems

In this paper, a low resistance grounded system is one in which the neutral resistor limits the current to values between 15 A and 20 pct of the maximum available three-phase short-circuit current.

High Resistance Grounded Systems

This is a system in which a high value resistor has been inserted in the neutral connection to ground to limit the resistor current under ground fault conditions to a value not less than the system changing current.

The changing current is the current that flows from each phase conductor to ground through the distributed phase-to-ground capacitance due to the phase-to-neutral voltage impressed across the capacitance.

For the purpose of this paper, a high-resistance grounded system is one in which the neutral resistor limits the current to 15 amperes or less, but not less than the system charging current (fig. 3).

Solidly Grounded System

The solidly grounded system is a system in which the neutral point is connected directly to ground with no intentional impedance in the ground connection and therefore no intentional limitation of ground fault current magnitude (fig. 4).

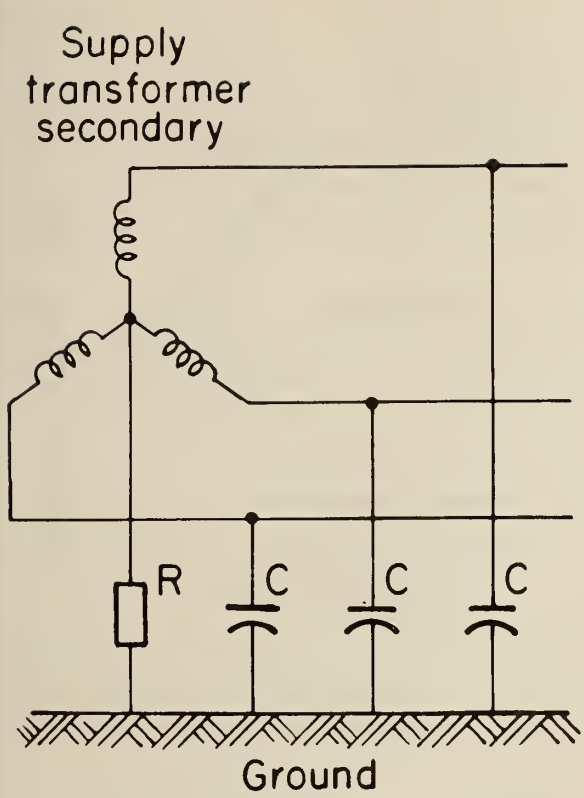


FIGURE 3. - Resistance grounded system.

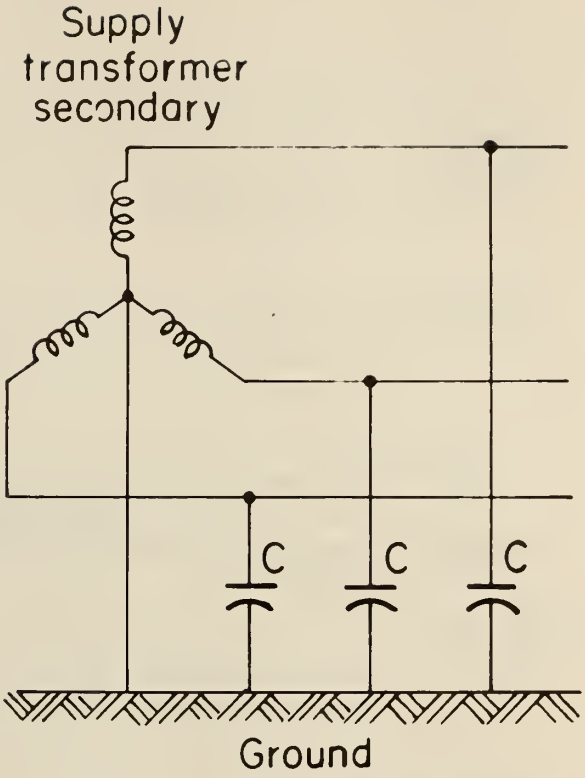


FIGURE 4. - Solidly grounded system.

ADVANTAGES AND DISADVANTAGES OF ISOLATED, RESISTANCE, AND SOLIDLY GROUNDED SYSTEMS

Presence of Line-to-Grounded Voltage

Under normal conditions, there is always a voltage present between the line conductors of all three systems and ground, or any grounded metallic objects such as frames, pipes, track rails, roof bolts, and conductors of other systems.

The isolated system, however, presents a special problem when a conductor becomes grounded. The following formula can be derived from figure 5.

$$I = (E/(3)^{1/2})/(R^2 + (1/3WC)^2)^{1/2},$$

where I = current through the body in amperes,

E = system voltage (line-to-line),

R = resistance of the body in ohms,

W = 377 for a 60-Hz system,

and C = total system capacitance.

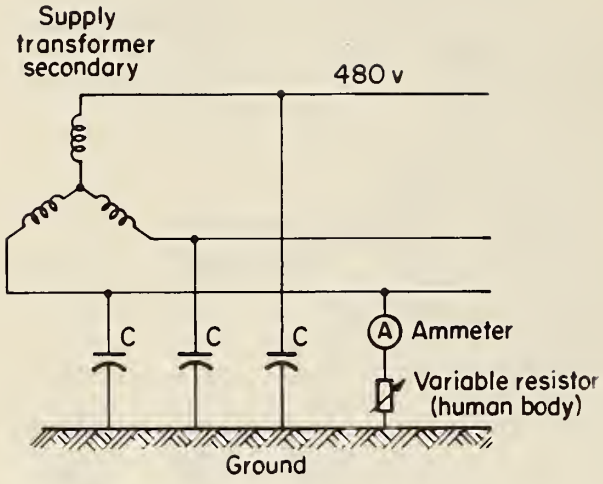


FIGURE 5. - Test connections simulating person in contact with ungrounded system.

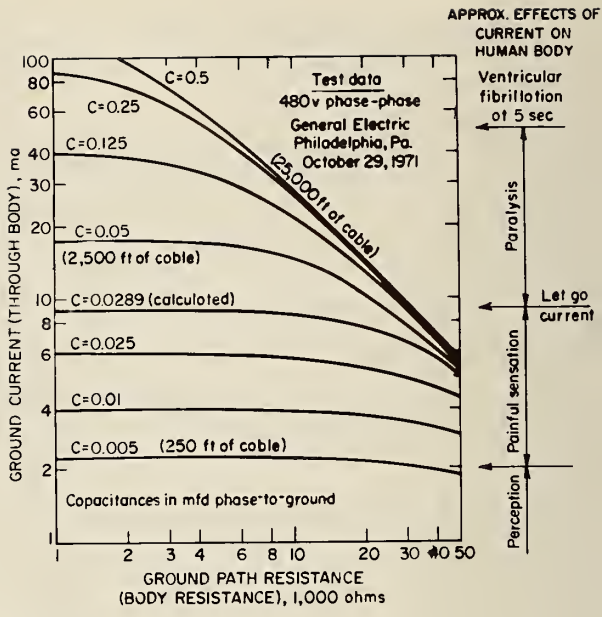


FIGURE 6. - Relationship between ungrounded system capacitance, body current, and body resistance.

Using this formula and taking the capacitance of a typical mining cable to be in the order of 0.02 μF per 1,000 feet, values of body current can be calculated. Figure 6 shows experimental values found by the General Electric Co.

One important conclusion that may be drawn is that a completely ungrounded system is no safer than any other system from the standpoint of a personnel shock hazard. It may even be less safe because some personnel simply assume it is safe since it is not intentionally connected to ground.

Subject to Excessive Overvoltage

The voltage between line and ground may rise to values several times the voltage rating of the system under certain abnormal but not necessarily unusual conditions. The two conditions that can cause overvoltages in coal mine power distribution systems are (1) physical contact with a higher voltage system and (2) switching surges.

Physical Contact With a Higher Voltage System

If the conductors of a high-voltage circuit come into contact with those of a lower voltage circuit, then the same potential will exist on both circuits at the point of contact. If the low-voltage circuit does not have its neutral grounded, its potential will be increased to that of the high-voltage system or flashover will occur. If the low-voltage system is anchored close to ground potential by the use of a solidly grounded neutral, high values of current may flow from the high voltage system, but at the same time, much lower voltages will appear than with an ungrounded system.

Switching Surges

There are several ways in which switching operations can cause transient overvoltages in nearly all types of systems, but the ungrounded system is particularly vulnerable to transients due to the unequal closing times of the poles of the breaker in the primary of the transformer supplying the ungrounded system (fig. 7). If phase A closes first, the circuit given in figure 8 applies.

The voltage to ground on the 480-volt secondary winding, and whatever might be connected to it, is 2,700 volts until poles B and C of the breaker close. Such repeated overvoltage transients weaken insulation to cause premature breakdown.

To minimize the transfer of transient overvoltages from the primary circuits to the secondary low-voltage system, the transformer should be provided with a Faraday shield between the primary and secondary windings. This shield is a turn of metal sheet placed between the windings, insulated from all windings and connected solidly to ground. Such a shield not only minimizes the transfer of disturbances from the primary to secondary windings but prevents a short circuit between the two sets of windings. In other words, it prevents the low-voltage windings from coming into contact with the high-voltage windings due to an internal fault in the transformer. The shield does not increase transformer cost significantly if specified before manufacture.

First-Ground Fault Current Magnitudes

The only current that flows through a ground fault in an underground system (fig. 9) is the charging current of the system capacitance.

In the resistance grounded system (fig. 10), the ground fault current is limited to the desired low value by the choice of the neutral resistor.

In the solidly grounded system, a very high fault current flows, approaching the magnitude of the current in a three-phase short circuit.

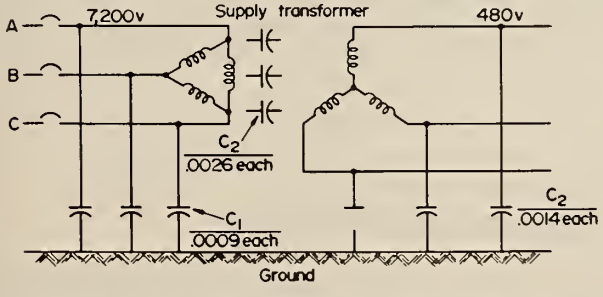


FIGURE 7. - Illustration of conditions producing switching transients due to unequal pole closing of transformer primary breaker.

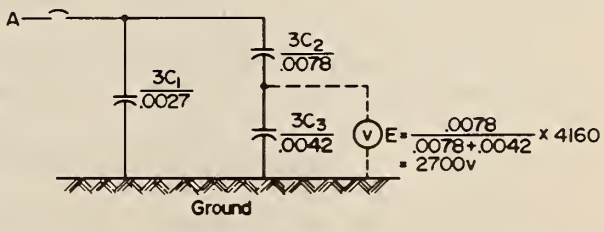


FIGURE 8. - Equivalent circuit diagram of unequal pole closing of primary breaker.

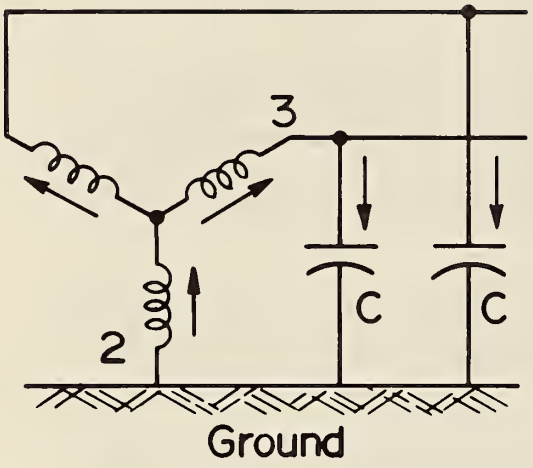


FIGURE 9. - Ungrounded system with ground fault on one line.

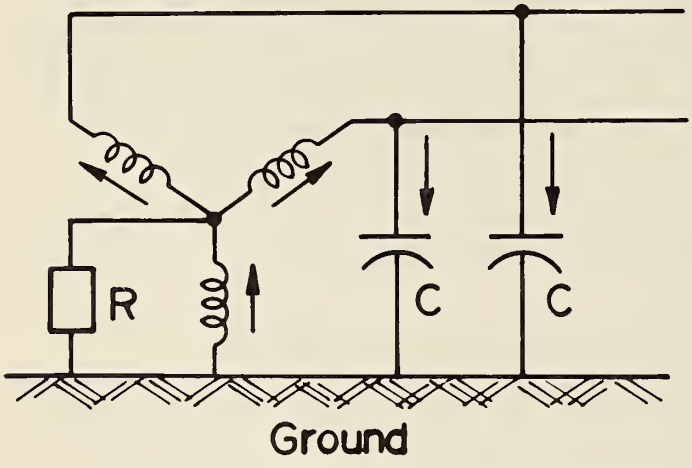


FIGURE 10. - Resistance grounded system with ground fault on one line.

Rise in Voltage on First Ground Fault

The first solid line-to-ground connection will cause the voltage between the line conductor and ground at the point of the fault to fall to zero. The voltage between each of the other two phases and ground will rise to full line-to-line voltage (fig. 11).

As can be seen from figure 11, all of the insulation on phases 1 and 3 of the system are stressed at 1.73 times the voltage stresses under normal operating conditions.

For a high-resistance grounded system, the first solid ground fault will have the same result. The fault current will be somewhat higher depending on the ohmic value of the neutral resistor.

On the solidly grounded system, a very high fault current flows. The voltage of the other two phases will not rise and, in fact, will drop owing to the high current flowing through the system impedance.

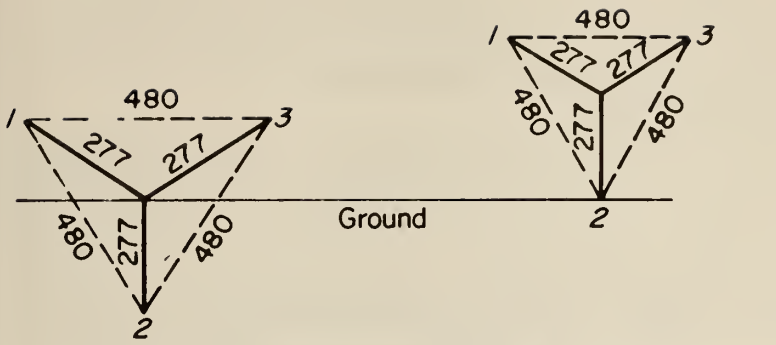
First Ground Fault Does Not Affect System Operation

The first line-to-ground fault on an ungrounded system will not affect the operation of the system as long as it is a solid connection to ground and no other phase of the system has a ground fault on it. The same is true of the high-resistance grounded system except that the ground fault current may be somewhat higher.

In the case of the solidly grounded system, the fault current is so high that overcurrent protective devices operate to de-energize the circuit.

Second Ground Fault Causes System Short-Circuit

The second solid line-to-ground fault on the same system, occurring on one of the other two phases before the first line-to-ground fault is cleared, will cause a double line-to-ground fault (line-to-ground-to-line) (figs. 12-13).



(a) Normal (b) Line-to-ground fault

FIGURE 11. - Ungrounded system voltage vectors under normal and line-to-ground fault conditions.

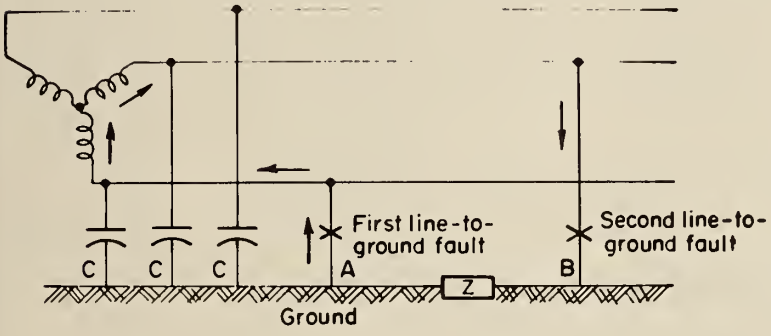


FIGURE 12. - Double line-to-ground fault on ungrounded system.

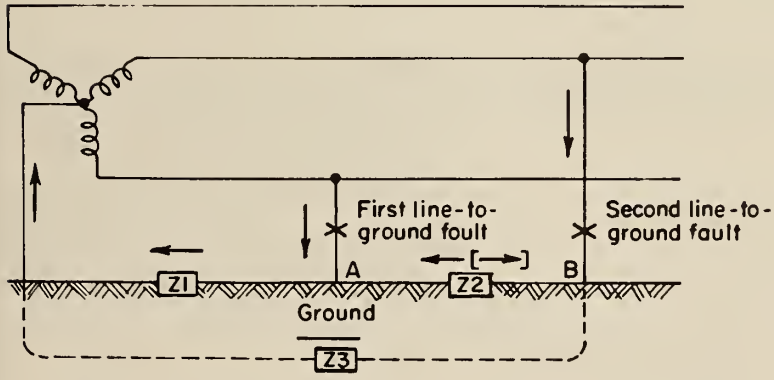


FIGURE 13. - Double line-to-ground fault on solidly grounded system.

Initial Cost

The initial cost of an ungrounded system is lower than the cost of any other type of system. However, the difference in cost is not very much and, therefore, is not an important factor in system design.

Maintenance, Repair, and Downtime Cost

The cost of trouble-shooting, repair and maintenance, and the cost of loss of production during downtime could be high for the ungrounded system for several reasons.

Since the magnitude of the fault current on an ungrounded system is low for the first line-to-ground fault, troubleshooting time may be costly in terms of labor and loss of production.

If the system remains in operation after the first fault occurs, a second fault may occur, and the resulting damage may be very severe. This increase in cost for repairs may not have been incurred if the first fault had been removed promptly.

In the case of the high-resistance grounded system, the first line-to-ground fault will not be pinpointed by any visible evidence either. However, the use of ground fault detectors on each circuit of a high-resistance grounded system will give an immediate indication of the first line-to-ground fault.

For the solidly grounded system, the first line-to-ground fault will cause overcurrent trip devices to operate. The high fault current may cause considerable damage due to intensive arcing, resulting in possible higher repair costs or even equipment replacement.

It is evident from the previous discussion and tables 1-2 that the high resistance grounded system is the best choice of grounding for coal mine power systems.

TABLE 1. - Advantages and disadvantages of ungrounded system

Characteristic of ungrounded system	Advantages or disadvantages of ungrounded system, relative to--		
	High-resistance grounded system	Low-resistance grounded system	Solidly grounded system
1. Presence of line-to-ground voltage normally.....	N	N	N
2. Subject to excessive overvoltage.	D	D	D
3. First-ground fault current magnitude.....	N	A	A
4. Rise in voltage on first ground fault.....	N	N	D
5. First ground fault does not affect operation.....	N	A	A
6. Second ground fault causes system short circuit.....	N	N	N
7. Initial cost.....	A	A	A
8. Maintenance, repair, and downtime cost.....	D	D	(1)

A = Advantage. D = Disadvantage. N = Neither.

[1] Depends on nature and severity of fault.

TABLE 2. - Advantages and disadvantages of high-resistance grounded system

Characteristic of ungrounded system	Advantages and disadvantages of high-resistance grounded systems relative to--		
	Ungrounded system	Low-resistance grounded system	Solidly grounded system
1. Presence of line-to-ground voltage normally	N	N	N
2. Subject to excessive overvoltage.....	A	N	N
3. First ground fault current magnitude.....	N	A	A
4. Rise in voltage on first ground fault.....	N	N	D
5. First ground fault does not affect system operation.....	N	A	A
6. Second ground fault causes system short-circuit.....	N	N	N
7. Initial cost.....	D	N	N
8. Maintenance, repair, and downtime cost.....	A	A	A

A = Advantage. D = Disadvantage. N = Neither.

The effects of transients on the grounding system, personnel, and equipment will now be discussed.

UNDERGROUND COAL MINE POWER SYSTEM TRANSIENTS

With a grant from the Federal Bureau of Mines, the Department of Mineral Engineering of Pennsylvania State University is conducting underground coal mine power system transient measurements. This work is not completed at this time. However, preliminary measurements verify what was already suspected; underground coal mine power systems are subjected to very high transient voltages. A rule-of-thumb method that may be used to calculate the magnitude of these transients on the high side of the load center is given:

Line-to-ground transients: 5.3 times peak line-to-ground voltage.
Line-to-line transients: 5.3 times peak line-to-line voltage.

For example, on a 12.47-kV high side, line-to-ground transients of 53.96 kV are possible, and line-to-line transients of 93.47 kV are possible. On a 7.2-kV high side, line-to-ground transients of 31.16 kV are possible, and line-to-line transients of 53.97 kV are possible. These figures for line-to-ground and line-to-line transients are conservative, and values of 10 to 20 pct higher are possible.

These transients were seen to occur in a 2-msec window containing 25 to 100 spikes. The repetition rate of these 2-msec packets of spikes is one burst every 3 to 5 min.

Coupling of Transients Through Transformers

The following is an estimate of the magnitude of the transient that is coupled from the primary to the secondary of a 7.2-kV to 480-Vac power transformer (fig. 14).

The transient frequency is assumed to be 1 MHz.

VT = the line-to-ground transient voltage.

V = the voltage from one secondary phase to ground.

C1 = capacitance between primary and ground.

C2 = capacitance between primary and secondary phase windings.

C3 = capacitance between secondary and ground.

VT = 31.16 kV (as found previously).

IT = total transient current.

$$V = \frac{XC3}{XC2 + XC3};\ VT = \frac{3.7894E1}{3.7894E1 + 2.0404E1}\ VT.$$

V = (.65) VT, therefore for VT = 31.16 kV.

V = 20.254 kV.

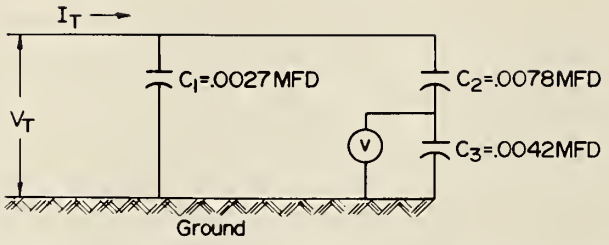


FIGURE 14. - Equivalent circuit of the capacitance coupling of a line-to-ground transient through a transformer.

Therefore, any equipment or personnel coming into contact with a secondary conductor and ground could be subjected to voltages as high as 20 kV. The insulation of transformers, cables, and motors will also be stressed and weakened after being subjected to these transients over long periods of time.

The equivalent circuit for the coupling of a transient from line-to-line is as shown in figure 15.

$$C12 = \frac{C1\ C2}{C1 + C2} = 9.1E\text{-}10$$

$$C34 = C12 = 9.1E\text{-}10$$

$$C125 = C346 = 18.1E\text{-}10$$

CT (total circuit capacitance) = C123456 = 9.05E-10

$$ZT = \frac{1}{JWCT} = 1.7586E2 \angle -90°, \quad W = 2\pi F, \quad F = 1MHz$$

$$IT = \frac{VT}{ZT} = \frac{53.97E3}{1.7586E2} \angle 90° = 3.0689E2 \angle 90°$$

$$I_1 = \frac{Z5}{Z_{12} + Z5} IT = 1.5429E2 \angle 90°$$

VC2 = I1ZC2 = 1.754E4 = VC3

V = VC2 + VC3 = 35.08 kV

Therefore, 35.08 kV will be coupled line-to-line from the primary to the secondary of the 7.2-kV load center transformer. Any loads connected line-to-line will be subjected to this voltage.

The origin of these transients are not known for certain at this time. However, it is believed that many of them originate from the power delivered to the mines.

One known source of transients in coal mine power systems is the 250-Vdc contactor. Using a JOY A40537 250-Vdc coil, transient voltages as high as 5 kV were measured in the laboratory. The test circuit is shown in figure 16.

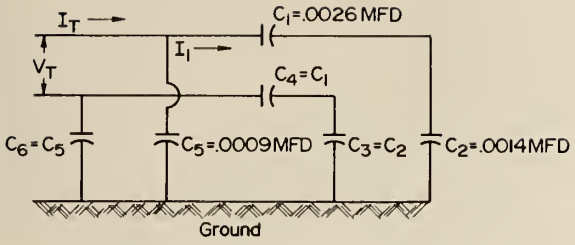


FIGURE 15. - Equivalent circuit of the capacitive coupling of a line-to-line transient through a transformer.

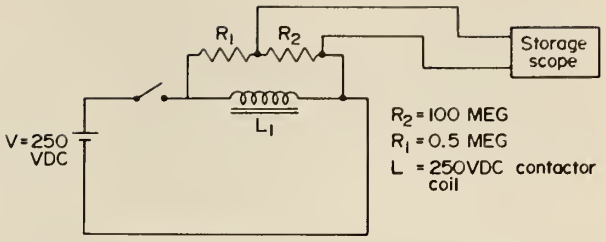


FIGURE 16. - Test circuit for 250-V dc contactor.

To suppress these contactor transients, three 200-volt transient suppressors, manufactured by MCG Electronics Inc.,[2] were connected across the coil. With the suppressors in place, the transients now measure approximately 370 volts or only 120 volts above the normal line voltage. It should be noted that the elimination of transients at their source is the preferred method of transient protection.

The Federal Bureau of Mines is now evaluating other methods and devices that can be used to eliminate transients. As was previously mentioned, the coupling of transients from the primary to the secondary of a transformer can be minimized by using a Faraday shield between the primary and secondary windings.

Effects of Transients on Personnel and Equipment

How these transient voltages can affect personnel depends, in general, on the condition of the grounding system, the magnitude and duration of the transient, the resistance of the human body (both contact and bulk body resistance), and the circuit elements involved.

It is evident from the previous calculations that any electronic equipment powered from the 480-Vac system must have very extensive transient protection. Great care must be taken whenever any electronic equipment is installed in an underground coal mine power system.

A good case in point is the FEMCO ground monitor (fig. 17), which connects an L-C filter from one phase conductor to ground on the machine that is having its ground wire monitored.

The effects of transients on R-L-C networks were studies using a computer circuit analysis program. Impulses as shown in figure 18 were applied to these networks. The results of these tests can be found in appendix A.

[2]Reference to specific manufacturers does not imply endorsement by the Bureau of Mines.

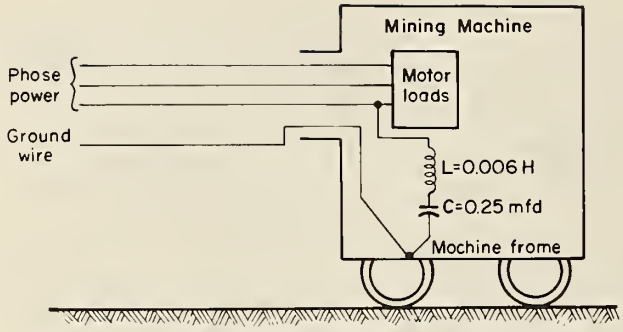


FIGURE 17. - Machine-mounted filter for FEMCO ground monitor.

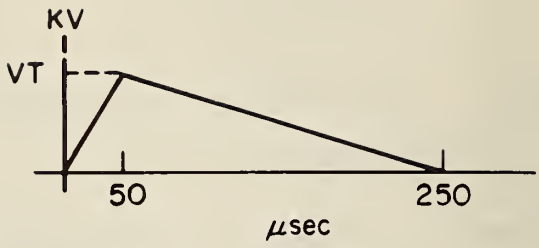


FIGURE 18. - Applied transient voltage.

For case 1, in the appendix, VT = 10 kV, the capacitor is subjected to 2,328.26 volts above its maximum working level for 1 msec and a peak voltage of 7,940.24 volts. This may not be a voltage of sufficient value to damage the capacitor. However, since the insulation properties of dielectrics decrease with increasing temperature and frequency of the applied voltage, and since case insulation tests for capacitors are conventionally conducted at high-pot dc voltages or at powerline frequencies, and since transients of this level occur quite often in coal mines, the capacitor dielectric will be weakened and the capacitor will eventually fail.

If a resistor of 1,000 ohms is used in place of the 19-ohm grounding resistor and all other parameters remain constant, the capacitor is now subjected to 1,909.55 volts below its maximum working level and a peak voltage of only 231.98 volts above the maximum working level. A high-resistance grounding system will, therefore, aid in the protection of electronic equipment connected line-to-ground from line-to-ground transients.

Placing an inductor in line with the circuit to be protected is a common practice in transient suppression. A comparison of the test results found in the appendix bears out this fact. For example, with R = 19 ohms, L = 0.006H, C = 0.25 μF, VT = 10 kV, then VC = 5,328.25 volts or 3.55E-3 joules absorbed by the capacitor. With R = 19 ohms, L = 1.4 H, C-0.25 μF, VT = 10 kV, then VC = 1,149.5 volts or 1.65E-3 joules absorbed by the capacitor.

Therefore, the 1.4 H inductor decreased the average voltage across the capacitor by 74.42 pct. However, the energy absorbed by the capacitor was decreased by only 53.52 pct.

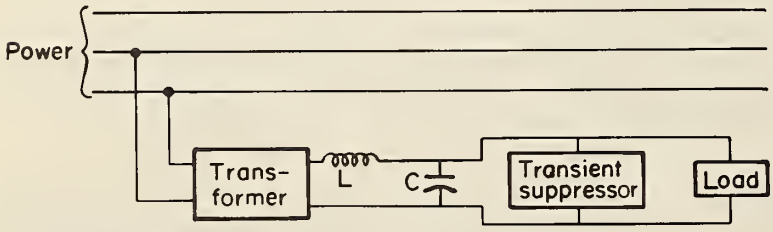


FIGURE 19. - Transient suppression for electronic equipment protection.

Any effort to protect electronic equipment from power system transients (usually line-to-line) should probably consist of a combination of inductors, capacitors, and transient suppressors as shown in figure 19.

The fact that transients can and do affect electronic equipment is well documented. However, can transients be a danger to personnel? On the basis of tests run at Columbia University, Ferris, King, Spence, and Williams suggested 100 mA as the fibrillation threshold where shock duration is not specified. An examination of the test data in the appendix indicates that for every case where R equals 1,000 ohms (body resistance plus any ground resistance) the current through the body is greater than 100 mA.

Under the ideal conditions of good cable insulation and continuity of the ground conductor, transient voltages would be of little direct danger to personnel. However, the presence of transient voltages of 20 kV and higher will deteriorate cable insulation to the point where a dangerous situation could exist. Such a situation could be the following: A man is standing with one foot on an energized cable and his other foot on the ground; the cable insulation at this point is poor resulting in a current flow of 100 mA or greater through the body. This level of current could cause fibrillation or could cause the man to fall or become tangled in machinery due to a reflex action. One point that should be mentioned here is that if shielded cable were used in this instance, and the shields were intact, an accident of this nature would not occur.

CONCLUSION

When current levels as low as 9.0 mA must be considered as dangerous, great care must be taken in the type of grounding system employed and the monitoring of this system. The high-resistance grounded system gives the best protection from both a personnel and an equipment standpoint.

The protection of equipment from transient voltages is a necessity. A first step in this area is the identification of transients, their source, and their levels. Second, an attempt must be made to eliminate the transients at their source. New transformers should be specified with Faraday shields, and transient suppressors must be used to suppress contactor transients. Third, all electronic equipment powered from the coal mine power system must have adequate transient suppression to insure reliability.

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APPENDIX

The equivalent circuit for the R-L-C networks tested is given in figure A-1.

R = circuit resistance.

L = circuit inductance.

C = circuit capacitance.

T = total time of simulation.

VT = applied transient voltage.

I = total circuit current.

The following results were obtained:

Case 1: R = 19 ohms L = 0.006 H C = 0.25 F T = 1 msec VT = 5 kV

	Average values	Peak values
	VR = 269.88	614.34
	VC = 2,570.55	7,500.00
	VL = 2,049.86	4,495.30
	I = 14.20	32.33
VT = 10 kV		
	VR = 523.89	1,250.00
	VC = 5,328.26	7,940.24
	VL = 4,329.84	8,981.85
	I = 27.57	65.79

Case 2: R = 1,000 ohms L = 0.006 H C = 0.25 μF T = 1 msec VT = 5 kV

	Average values	Peak values
	VR = 2,099.55	4,343.93
	VC = 543.43	1,616.65
	VL = 269.54	559.26
	I = 2.10	4.34
VT = 10 kV		
	VR = 4,253.13	9,627.06
	VC = 1,090.45	3,231.98
	VL = 537.10	1,118.83
	I = 4.25	9.63

Case 3: R = 19 ohms L = 1.4 H C = 0.25 μF T = 10 msec VT = 10 kV

	Average values	Peak values
VR =	10.45	16.35
VC =	1,149.53	2,077.79
VL =	3,388.02	10,000.00
I =	550.42E-3	860.70E-3

Case 4: R = 1,000 ohms L = 1.4 H C = 0.25 μF T = 10 msec VT = 10 kV

	Average values	Peak values
VR =	330.61	774.32
VC =	502.48	1,564.85
VL =	3,608.95	10,000.00
I =	330.61E-3	774.32E-3

Case 5: R = 19 ohms L = 0.006 H C = 0.09 μF T = 1 msec VT = 10 kV

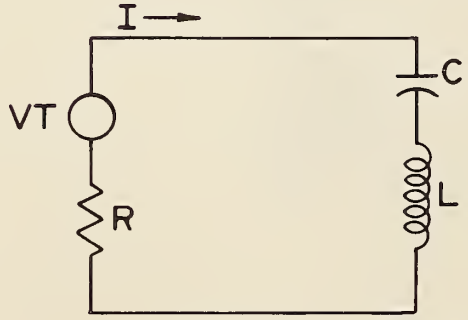
	Average values	Peak values
VR =	270.55	559.70
VC =	4,802.30	16,082.20
VL =	3,336.28	8,238.98
I =	14.24	30.46

Case 6: R = 1,000 ohms L = 0.006 H C = 0.09 μF T = 1 msec VT = 10 kV

	Average values	Peak values
VR =	3,370.60	7,503.80
VC =	40.89	5,682.92
VL =	493.11	1,043.29
I =	3.37	7.50

Case 7: R = 1,000 ohms L = 0.001 H C = 0.09 μF T = 1 msec VT = 10 kV

	Average values	Peak values
VR =	3,432.02	7,639.93
VC =	1,500.85	5,537.53
VL =	103.40	192.20
I =	3.43	7.64



R = circuit resistance
C = circuit capacitance
L = circuit inductance
T = total time of simulation
VT = peak transient voltage
I = total current

FIGURE A-1. - Test circuit for computer simulation.

APPLICATION OF MOLDED CASE BREAKERS ON DC ELECTRICAL SYSTEMS IN COAL MINES

by

A. B. Shimp[1] and D. A. Paice[2]

ABSTRACT

A test program was conducted to determine the adequacy of molded case circuit breakers for dc electrical systems in coal mines. Mine electrical system parameters and the most severe operating conditions to be expected were determined. Tests of the interrupting capabilities of several molded case breakers were made under the worst conditions to be expected. Continuous and pulsed current carrying capability of the breakers was also investigated. Breakers from two different manufacturers passed all tests successfully.

Based on the results of these tests, a set of guidelines for applying molded case breakers to dc systems has been prepared.

INTRODUCTION

There is little application data available on molded case circuit breakers applied on dc, particularly at 600 volts, because these breakers are designed primarily for use on ac circuits. It is well known, however, that a dc circuit is more difficult to interrupt than an ac circuit. Because of this lack of application data, a test program was sponsored by the Federal Bureau of Mines to determine the adequacy of molded case circuit breakers on dc electrical systems in coal mines.

The program had three objectives:

1. Define the dc electrical system parameters under which protective devices must operate in a coal mine.

2. Determine currently available molded case circuit breakers expected to be applicable for 300-volt, 2,500-ampere and 600-volt, 1,200-ampere mine service.

3. Verify by test the degree of adequacy of the circuit breakers identified in objective 2 to perform fault current interruption at the current levels defined in objective 1. The steady-state current carrying capability of the breakers was also to be investigated.

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[1]Senior engineer.

[2]Fellow engineer.

Both authors are with Westinghouse Electric Corp., Research and Development Center, Pittsburgh, Pa.

As a result of this program, a set of application guidelines for molded case breakers on dc electrical systems has been prepared.

ACKNOWLEDGMENTS

The work described was carried out under Federal Bureau of Mines Contract No. H0122058, with E. Litchfield of the Bureau of Mines acting as the technical project officer and R. P. Putkovich of the Westinghouse Electric Corp. as the project manager. The assistance given by these people and also by J. Murphy of the Bureau of Mines and A. Cellerini of the Westinghouse Distribution and Control Equipment Div. at Beavery, Pa., is gratefully acknowledged.

CURRENT INTERRUPTION IN A DC CIRCUIT

Interruption of current in a dc circuit is more difficult than in an ac current because there is no natural current zero and the dircuit breaker must force the current to zero.

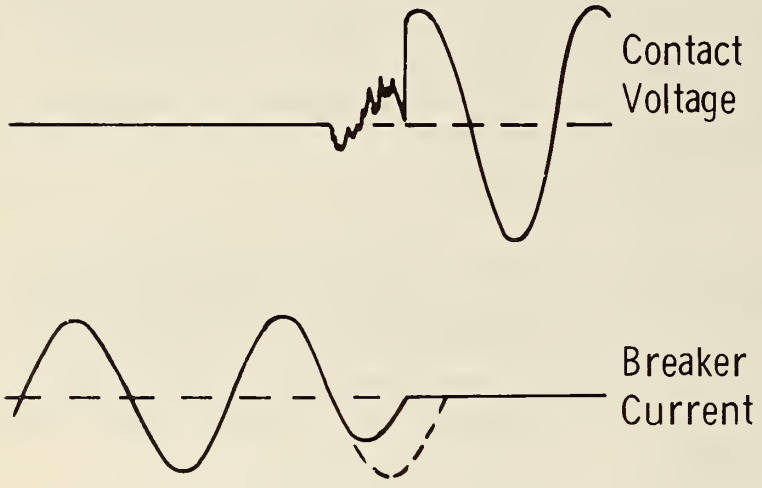


FIGURE 1. - Illustrating an ac interruption.

A typical ac circuit interruption is illustrated in figure 1. At the instants of current zero, which occur twice during each cycle, a relatively small arc voltage across the breaker contacts is sufficient to extinguish the current.

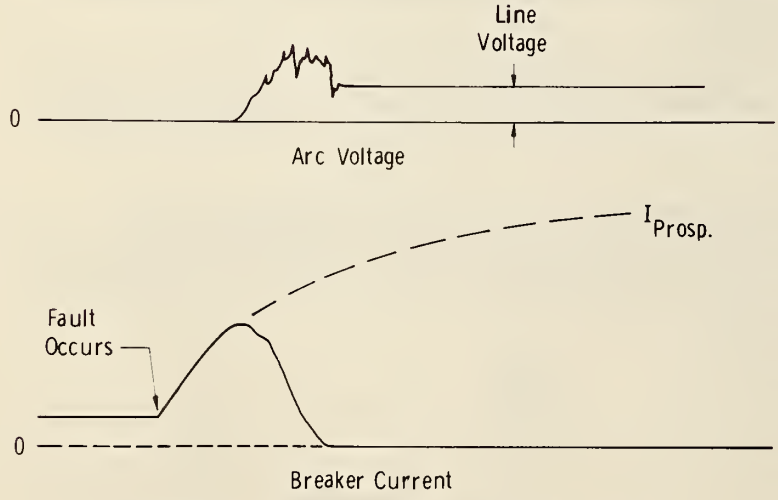


FIGURE 2. - Illustrating a dc interruption.

Compare this with a dc circuit interruption, which is illustrated in figure 2. In this case, an arc voltage greater than the line voltage is necessary to drive the current to zero. If the arc voltage is less than the line voltage, the current will continue to flow through the breaker. During the time that an arc exists across the breaker contacts, energy in the form of heat is being dissipated. The two most important factors that determine the amount of energy dissipated and therefore the severity of a dc interruption are the value of the current to be

interrupted and the circuit inductance. Typical values of these parameters on dc systems in coal mines have been determined.

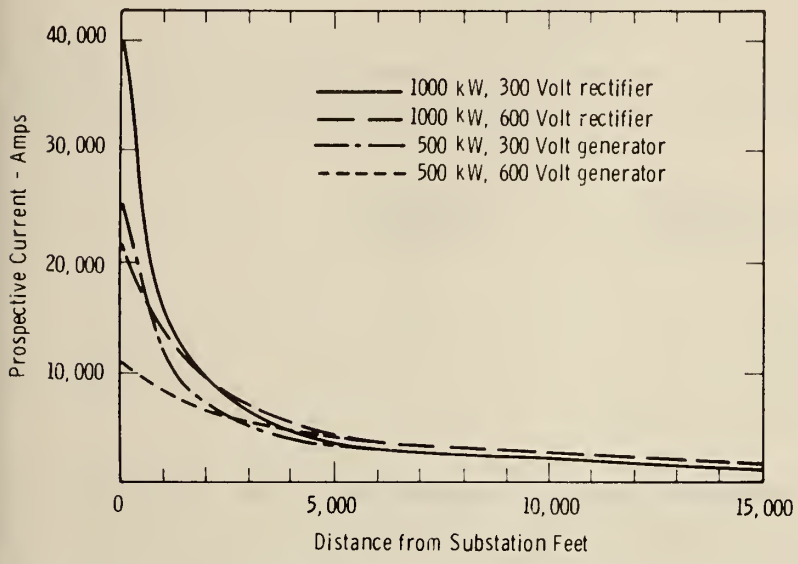


FIGURE 3. - Prospective current versus distance from substation.

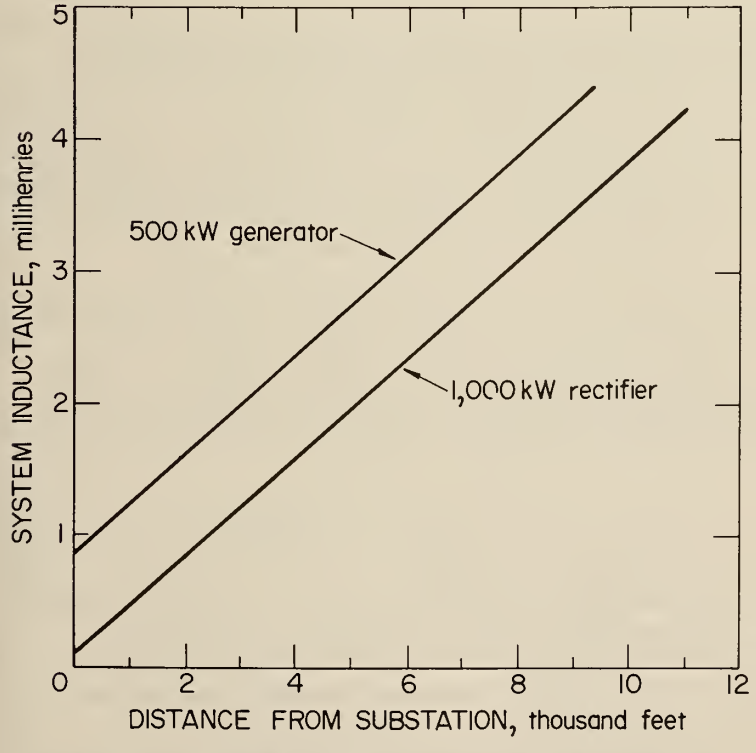


FIGURE 4. - System inductance versus distance from substation.

CHARACTERISTICS OF MINE DC ELECTRICAL SYSTEMS

Mine electrical systems differ widely depending upon the particular mine, and it is difficult to define a general arrangement. A mine system may include all manner of ac-dc converting equipment operating singly or in parallel and interconnected with a wide variety of cable sizes and steel rails. The nominal dc voltage may be 300 volts or 600 volts.

The value of prospective current that will exist under a wide variety of conditions is illustrated in figure 3. Prospective current is defined as the final value of current that would be reached in a circuit if no interruption took place. It is seen that the prospective current varies from 10,000 to 40,000 amperes adjacent to a substation but decreases rapidly to only a few thousand amperes at distances of a mile or more from the substation.

In a similar manner, the circuit inductance that includes that of the substation plus the line inductance is illustrated in figure 4. Values from 0.2 to 2 mH are typical. This does not include the inductance of the loads, and many loads such as locomotives may have inductances comparable with this.

Since the mine system characteristics were known, a test program was set up to simulate actual operating conditions.

TEST PROGRAM

Five different types of molded case circuit breakers from three different domestic suppliers were obtained for test. The ratings of these breakers are tabulated as follows:

Continuous current rating, amperes	Number of poles
600	3
1,200	3
600	2
800	3
1,200	3

These breakers were representative samples suggested by the manufacturers as types that might be capable of satisfactory operation on 600 volts dc. They were designed for ac use, however, and had a dc rating of only 250 volts. The types tested do not necessarily include all the available molded case breakers that may be satisfactory for 300-volt and 600-volt dc service in coal mines.

The types of circuit breakers to be tested were equipped with adjustable, instantaneous magnetic trip units and shunt trip attachments. Laboratory tests indicated that for dc operation the instantaneous dc current at trip is about 1.3 times the ac rms trip current setting. A high-current, low-voltage ac power supply was used for setting the trip units of the circuit breakers. Subsequently, during high-power testing it was determined that the arrangement of power cables in the vicinity of the circuit breaker could modify the trip setting, and final adjustments were made on the high-power test rig.

The facilities of the Westinghouse East Pittsburgh plant were used for the hgih-power current interruption tests at rated voltage. Four dc generators were available in conjunction with a fairly wide range of inductance and resistance load banks and the generators could be operated either singly or in parallel as required. The rating of each dc generator was 1,500 kW at 750 volts.

Initially, a wide variety of high power tests was conducted to determine the most important factors affecting breaker adequacy. The low-current, high-inductance tests were particularly important because it was found that some circuit breakers performed satisfactorily at high current, but failed to interrupt at low current. The difficulty of interrupting a high-inductance circuit is illustrated in figures 5-6. Figure 5 is an oscillogram taken during a successful interruption by one breaker of 11,200-amperes in a current relatively low inductance circuit. Figure 6 illustrates the failure of this same breaker to interrupt a much lower current, 1,030 amperes, in a higher inductance circuit.

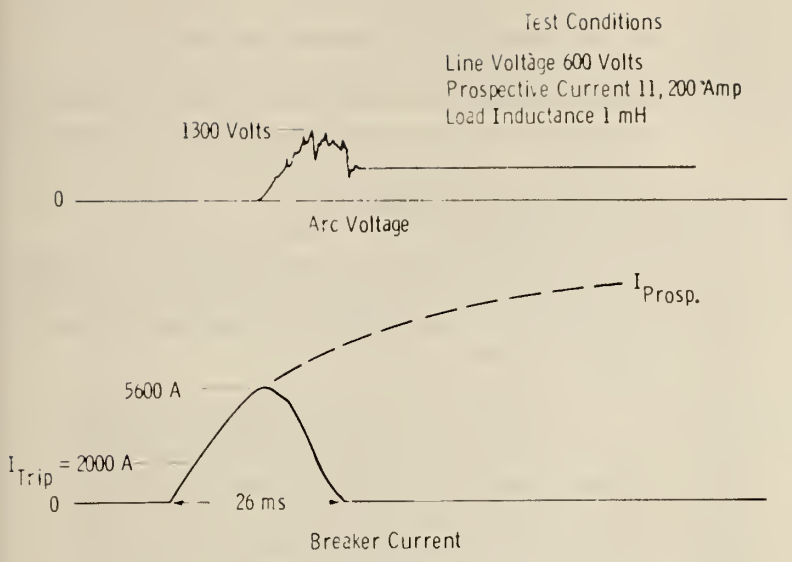


FIGURE 5. - Illustrating high-current interruption.

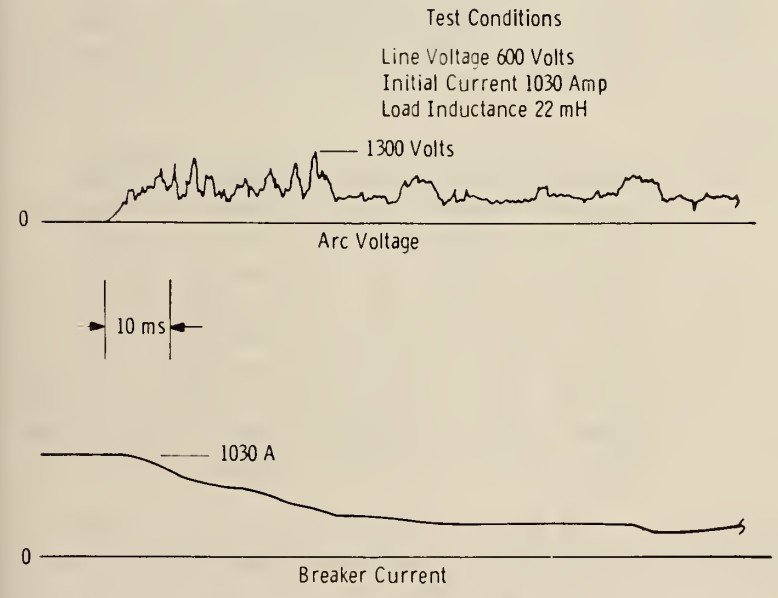


FIGURE 6. - Illustrating failure to interrupt a low-current, high-inductance fault.

Most loads connected to the trolley wire have a relatively high inductance. Because of the difficulty of interrupting currents in high-inductance loads, molded case breakers should not be used as switches to turn these loads on and off repeatedly.

An important factor is the considerable amount of arc plasma that is often ejected from the terminals at the arc chute end of the breaker during a high-power interruption. To prevent an arc over to ground, it is important to mount the breakers vertically with the arc chute end terminals at the top. An adequate space (12 inches) or insulation between the circuit breaker terminals and any grounded metal is necessary.

Proper connections of the breaker are very important to insure successful high-power interruptions. Not only must the connections be tight, but the proper number of poles must be connected in series and the interconnections must be made in a preferred manner. For 600-volt service, a three-pole breaker must be used with all three poles connected in series to obtain sufficient arc voltage. The poles should be interconnected as illustrated in figure 7 (long pole connection) to minimize the voltage stress between poles. The short pole connection, illustrated in figure 8, although easier to make, is undesirable because it imposes the arc voltage of two poles between two terminals. One of the types of breakers tested experienced a number of voltage breakdowns between terminals with the short pole connection until its interpole barrier insulation was improved.

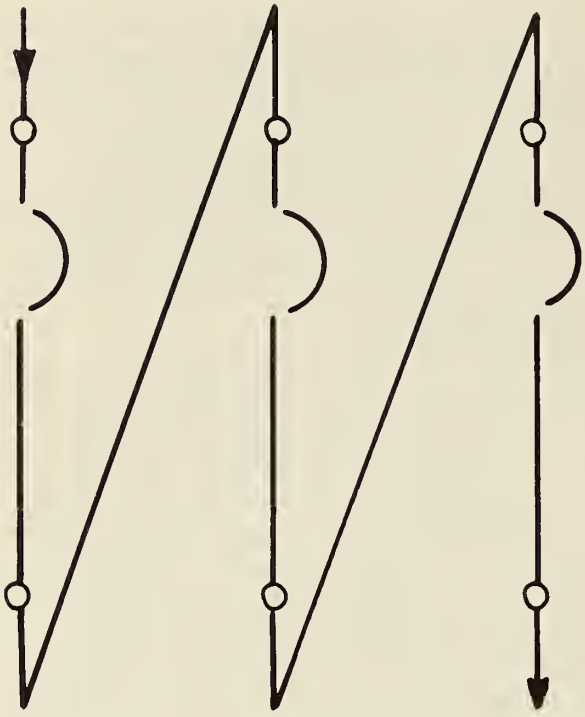


FIGURE 7. - Illustrating the proper interconnection for 600-volt service.

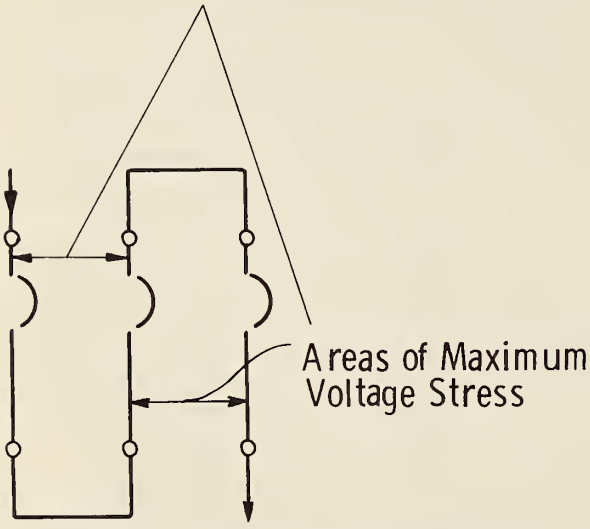


FIGURE 8. - Illustrating improper interconnection for 600-volt service.

For 300-volt service, either a two- or a three-pole breaker may be used. Only two poles should be connected in series; and the long pole interconnection, as illustrated in figure 9, should be used. Two poles provide sufficient arc voltage to interrupt the current on a 300-volt system. The use of three poles would cause an unnecessarily high voltage stress on other equipment connected to the 300-volt system when the breaker interrupts.

After the best method of mounting and connecting the breakers was determined from preliminary testing, the series of tests listed in table 1 was conducted on each of the five types of breakers. It was considered that a breaker should operate successfully at least twice at each test condition. Also, a further 30 operations for the conditions indicated by table footnote 2 should be completed satisfactorily.

Testing each of the five types of breakers per table 1 caused failures in two of the breaker types. In both of these failures, the breakers were unable to drive the current to zero although there was some current reduction. The failure was caused by low arc voltage, apparently because the arc did not move into the arc chute properly. Three types of breakers went through the whole series of tests satisfactorily.

A final series of tests was made to determine the electrical ruggedness and failure modes of the three satisfactory breakers. This was done by operating them repeatedly under high fault current conditions until failure occurred. The test procedure was more arduous than would be expected in practice. The breakers were operated fairly rapidly (at about 3-min intervals), and the voltage and currents were representative of severe operating conditions. The number of operations before failure occurred ranged from 68 to 97. In figure 10 are shown oscillograms taken at the beginning and near the end of the endurance test on one breaker. A reduced arc voltage and

extended interrupting time are evident at the end of the test. At the end of the test, the arc chutes were found to be badly pitted and burned; however, the breaker contacts were in relatively good condition. By periodically inspecting the arc chutes and replacing them when deterioration is evident, the life of the breaker can be prolonged.

TABLE 1. - Test conditions for candidate mine circuit breakers for 600-volt and 300-volt operation

Circuit breaker trip setting, amperes	Source voltage, volts	Prospective fault current, amperes	Fault inductance, mH	Fault time constant, msec	Energy stored after 18 msecs, kJ
2,000	600	24,200	1.0	40.3	38
2,000	600	24,000	.24	9.6	49
2,000	[1]630	11,200	1.0	17.8	25
([2])	600	1,400	19.0	44.0	[3]18.6
([2])	600	600	23.4	23.4	[3]4.2
4,000	300	27,200	.12	10.9	28
4,000	[1]300	19,500	.88	57.0	12.2
4,000	300	11,700	.88	34.4	9.9
([3])	300	1,100	23.7	87.0	[3]14.3

[1]32 operations of this condition should be completed satisfactorily.
[2]Shunt trip.
[3]At trip.

Following the high-power interruption tests, an investigation of the continuous current rating of the breakers was also made. The continuous rating of molded case ac circuit breakers is determined by temperature rise criteria of the connectors as defined in Underwriters Laboratories Standard UL 489. All of these molded case breakers meet this standard. In general, the continuous current rating must not cause a temperature rise of greater than 50° C at the breaker terminals. This corresponds under worst case conditions to a maximum temperature of 100° C at the connector and to a temperature at the contacts of about 125° C. The contact temperature is thought to represent a limiting feature, and practical engineering judgment indicates that for

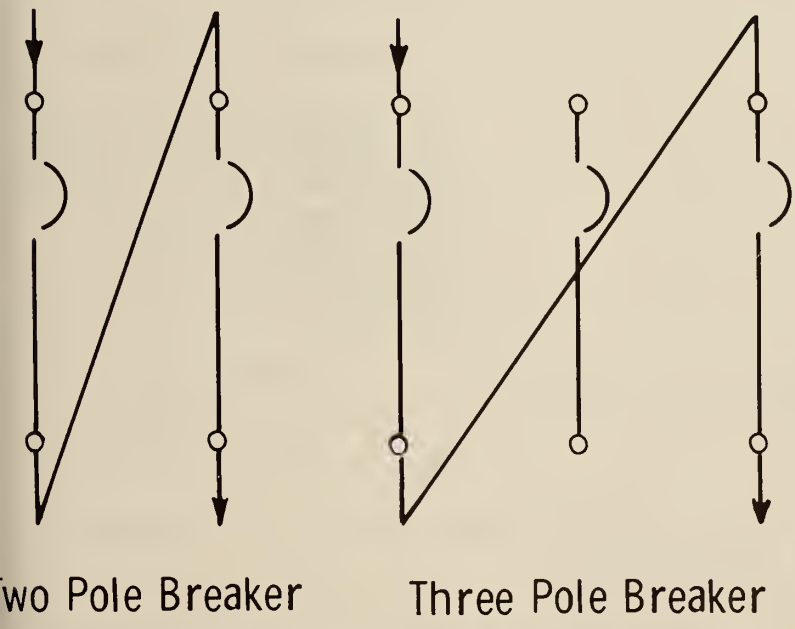
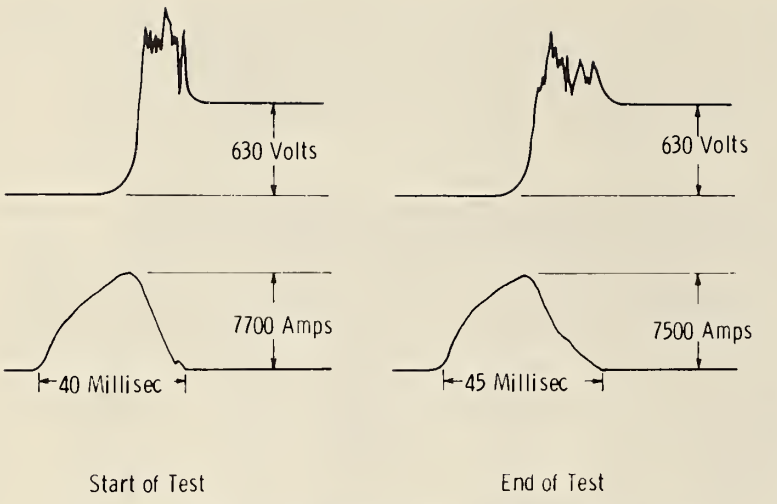
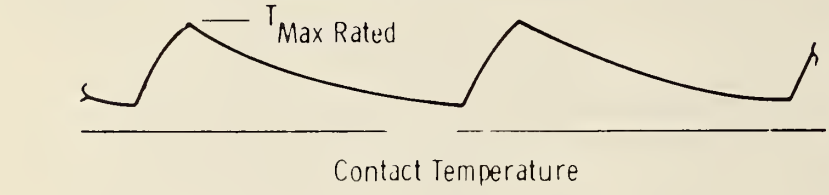


FIGURE 9. - Illustrating the proper interconnection for 300-volt service.



Upper Trace - Total breaker voltage - Lower Trace - Current
Test Conditions - 3 Poles in series
630 Volts DC - 11,200 Amps prospective current
Inductance 1 Millihenry

FIGURE 10. - Illustrating arc voltage change during endurance test.



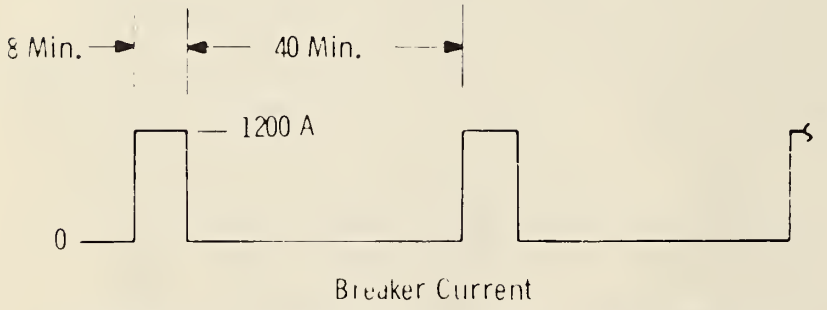


FIGURE 11. - Illustrating intermittent current capability of a 600-amp breaker.

satisfactory life, limits of 150° to 200° C should not be exceeded. Actual temperature rise is affected by the size of the connecting conductors, and these are defined in the Underwriters' specification.

In some cases, circuit breakers are subjected to intermittent peak currents with relatively small currents flowing between the peaks. Because of the thermal time constant of the breaker (about 35 min), it was found possible to subject a breaker to repeated short-duration peaks of current as high as twice rated value, as illustrated in figure 11, without exceeding safe operating temperatures. This is, of course, contingent on there being sufficient off time between peaks of current.

APPLICATION GUIDELINES

The following application guidelines for use of molded case circuit breakers on dc power systems are drawn up based on the results of both high- and low-power tests:

Connections

1. Keep connections tight.

2. Connect the poles in series so that current flows in the same way in each pole in order (long pole connection).

3. For 600-volt operation, use a three-pole breaker with all three poles connected in series.

4. For 300-volt operation, use either a two-pole breaker with both poles connected in series or a three-pole breaker with the two outer poles connected in series.

Mounting

1. Mount in an upright position.

2. Leave a 12-inch space or use insulation between the circuit breaker connectors and any grounded metal to prevent ejected arc plasma causing a flash over to ground.

Operation

1. Do not use molded case circuit breakers as on-off switches for normal mine loads.

2. Set the magnetic trips with interconnecting cables between poles laid out as in the actual application. Use the lowest value of trip setting possible consistent with freedom from nuisance tripping. Do not exceed 2,000-ampere trip settings for 600-volt, three-pole operation or 4,000-ampere trip setting for 300-volt, two-pole operation.

3. Be sure the breaker is rated to carry the expected load current without overheating.

4. Periodically check that the arc chutes are in good condition.

DISCRIMINATING PROTECTION FOR TROLLEY WIRES

by

D. A. Paice[1] and A. B. Shimp[2]

ABSTRACT

Illegitimate loads on a mine dc power distribution system can be detected by measuring a superimposed ac current. To implement such a scheme, a 10-volt, 3-kHz voltage is applied at each dc power substation. By this means, the mine dc power distribution network, consisting of a feeder and trolley wires with a grounded rail return, is caused to serve also as a 3-kHz ac distribution network.

Tuned current transformers encircling the dc feeder wires detect the presence of any 3-kHz currents and apply signals to trip appropriate discriminating circuit breakers when an illegitimate load of 20 ohms or less is detected across the trolley wire. High-power legitimate loads such as haulage locomotives are prevented from drawing 3-kHz current by means of a novel active filter. Other smaller loads are equipped with conventional 3-kHz filters.

INTRODUCTION

A trolley wire protection system similar to that described here was used in a French coal mine and is described in Cerchar Publication No. 1306--January, 1963. In this application, the trolley wire was powered by a single 500-volt dc substation. The system consisted of an oscillator that placed a 3,500-Hz signal on the dc trolley wire and detectors that measured the superimposed ac current to detect a fault. The maximum size haulage vehicle was about 80-hp rating, and protection of the trolley wire was obtained over a range of about 3 miles. This system could not be applied directly to the much larger American coal mines for three major reasons:

1. Typical American coal mines have several dc power substations operating in parallel.

2. The distances to be protected are much greater, typically 10 to 15 miles.

3. The haulage motors are much larger, up to 800 hp, and have a relatively low value of impedance at the superimposed ac frequency.

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[1]Fellow engineer.
[2]Senior engineer.
Both authors are with Westinghouse Electric Corp., Research and Development Center, Pittsburgh, Pa.

A study was made of other possible concepts that might provide trolley wire protection, but the basic concept of superimposing an ac signal on the dc system was deemed to be the most practical approach. The system was revised and improved to be applicable to American coal mines. The scheme is presently being installed to demonstrate its performance in 1-mile test sections of two operating coal mines.

ACKNOWLEDGMENTS

The work described was carried out under the U.S. Bureau of Mines Contract No. H0122058 with E. Litchfield of the Bureau of Mines acting as the technical project officer and R. P. Putkovich of the Westinghouse Electric Corp. as the project manager. The assistance given by these people, and also J. Murphy of the Bureau of Mines, is gratefully acknowledged.

John Burr and Dennis Gibbons of Lee Engineering, along with William Simpson and his coworkers at Consolidation Coal, helped with tests at the Renton mine. At the Cambria No. 33 mine of Bethlehem Mines Corp., the authors were helped by Terry Bender and John Ellis.

It is a pleasure to record the enthusiastic cooperation of these people and others in the coal mining industry.

SYSTEM OPERATING CONCEPT

The mine dc power distribution circuit consists of a feeder and trolley wire with a ground rail for return. Thus, it is basically a two-wire system, one conductor of which is grounded. By feeding a 10-volt, 3-kHz[3] signal between trolley wire and ground, the mine dc distribution system is also made to act as a two-wire ac distribution system with one grounded wire.

To detect the presence of undesired loads or faults (illegitimate loads) an air cored current transformer encircling the trolley wire is used to measure the amount of 3 kHz current. The signal from the current transformer supplies electronic circuitry that causes an appropriate circuit breaker to trip if an illegitimate load of 20 ohms or less is detected. The combination of current transformer, detecting circuitry, and circuit breaker has been termed a discriminating circuit breaker (DISCB). It discriminates between an illegitimate load such as a fallen trolley wire and a legitimate load such as a locomotive pulling a train load of coal. Conceptually, the technique is similar to conventional overcurrent protection of 60-Hz systems; however, because of the application, some additional problems are apparent. These problems and their solution are now discussed.

The legitimate loads such as haulage motors have a fairly low impedance in relation to the illegitimate loads it is desired to detect. For example, a 44-ton locomotive using four X 150-hp motors has an impedance of about 3 ohms at 3 kHz. Unless the impedance is increased, such a load would cause the

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[3]This frequency was selected after tests were made in a coal mine of various frequencies up to 20 kHz.

circuit breaker to trip. To overcome this difficulty, different techniques are used depending on the size of the equipment involved. For loads greater than about 35 hp, an active impedance multiplier is used to raise the impedance of the loads to greater than 100 ohms. The active impedance multiplier is currently the subject of a patent application. It is mounted on the vehicle and is essentially a closed-loop control system that minimizes the 3-kHz current flowing in the load. It requires a solid-state amplifier of about 100 watts for an 800-hp load. For smaller loads, such as lighting, or small motors, iron cored inductors are connected.in series with the loads such that the impedance is larger than 500 ohms at 3 kHz.

Rectifier units are often used to generate the mine dc power, and normal trolley wires contain appreciable harmonic voltages that could cause electrical noise problems. For example, in a 300-volt dc system, other voltages present could be 50 volts at 360 Hz, 16 volts at 720 Hz and 7 volts at 1,080 Hz. To avoid possible problems with unwanted signals, the detector and amplifying units of the discriminating circuit breaker are provided with filters to minimize the response to frequencies other than 3,000 Hz. A master oscillator maintains the detector system frequency at 3,000 Hz ±0.1 pct over the range of -25° C to +50° C and the filters are provided with temperature compensation to maintain an adequate accuracy.

In a normal mine system, there will be a number of substations, and each substation will have a low impedance to the 3-kHz signal applied to the trolley wire. To prevent the substation appearing as an illegitimate load, a power amplifier is used at each substation to supply 10 volts at 3 kHz to the trolley wire. Each amplifier is kept in synchronism by means of a signal from a master oscillator. Initially the oscillator signal has been distributed by separate twin conductor cables; however, other schemes that eliminate this cable may eventually be feasible. Amplitude and phase adjustments are provided in the power amplifier so that proper synchronization can be obtained and a minimum 3-kHz circulating current flows through the system due to interaction of power amplifiers. This technique of applying the 3-kHz signal at appropriate intervals throughout the mine also prevents excessive attenuation of fault signals that might otherwise be caused by the trolley wire inductance, which represents about 35 ohms per mile at 3 kHz.

In the event of an illegitimate load occurring, it is desired to interrupt power to the faulty mine section only. This can be done by using suitably spaced discriminating circuit breakers. In the event that a faulty section is isolated, the remaining mining system will retain protection because of the 3-kHz voltage applied by amplifiers at other substations.

An additional advantage of the discriminating circuit breaker concept is that it is possible to manually trip the dc power at any point in the mine. For example, trip signals can be generated by connecting a suitable impedance between trolley wire and rail, or by disabling an active impedance multiplier with a push button on the vehicle.

The system approach to the application of a discriminating circuit breaker (DISCB) is illustrated by means of figure 1.

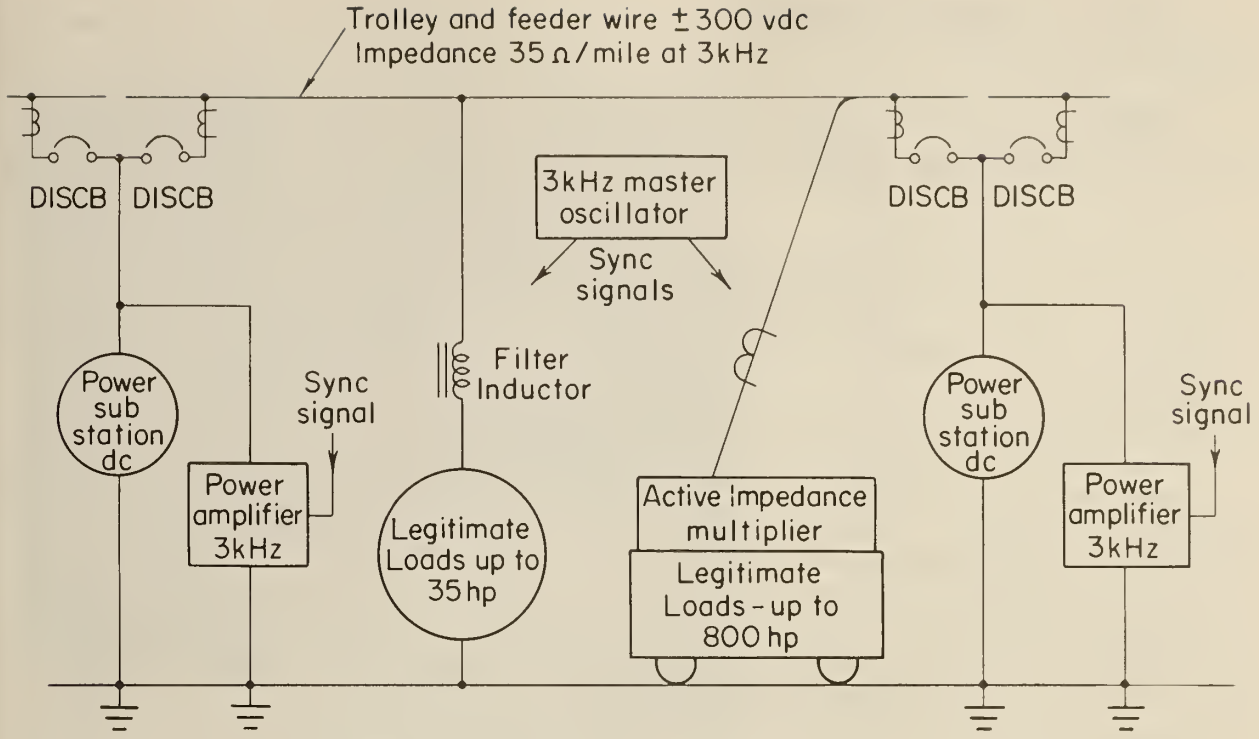

FIGURE 1. - Mine dc power system modified to incorporate discriminating circuit breaker to detect illegitimate loads. Additions to apply 3 kHz voltage to trolley wire.

SENSITIVITY TO ILLEGITIMATE LOADS

The sensitivity of the discriminating circuit breaker system is affected by which circuit breakers are closed and where the fault occurs. Figure 2 illustrates a typical system arrangement. It is observed that the inductive reactance X_L of the trolley wire and feeder cables will limit the flow of 3-kHz current. By calculation and underground measurement, it has been found that in the main haulageway the worst case value for X_L is about 35 ohms per mile. Using this value, the 3-kHz current for various values of illegitimate load has been calculated. The results for a typical 1-mile spacing between substations are plotted in figure 3.

It is observed that with a DISCB setting of 230 mA, a 20-ohm illegitimate load occurring anywhere between the substations will cause both the inby and outby circuit breakers to trip, thus disconnecting power to the fault.

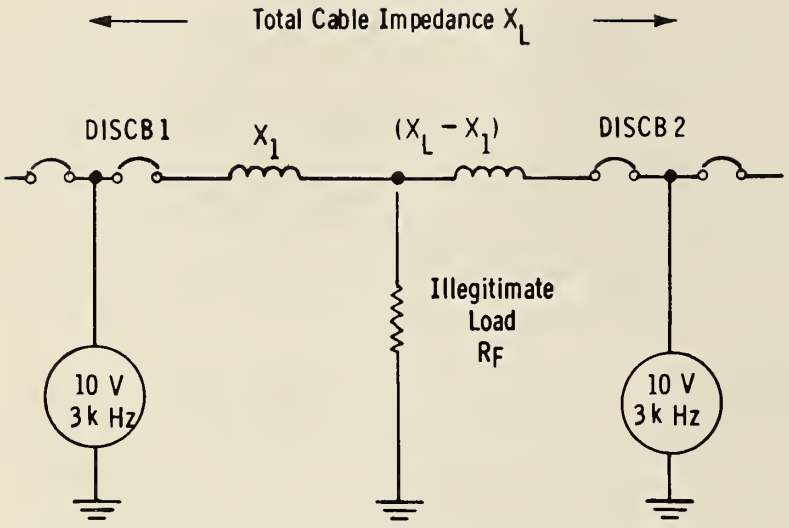

FIGURE 2. - Illustrating circuit for sensitivity calculation.

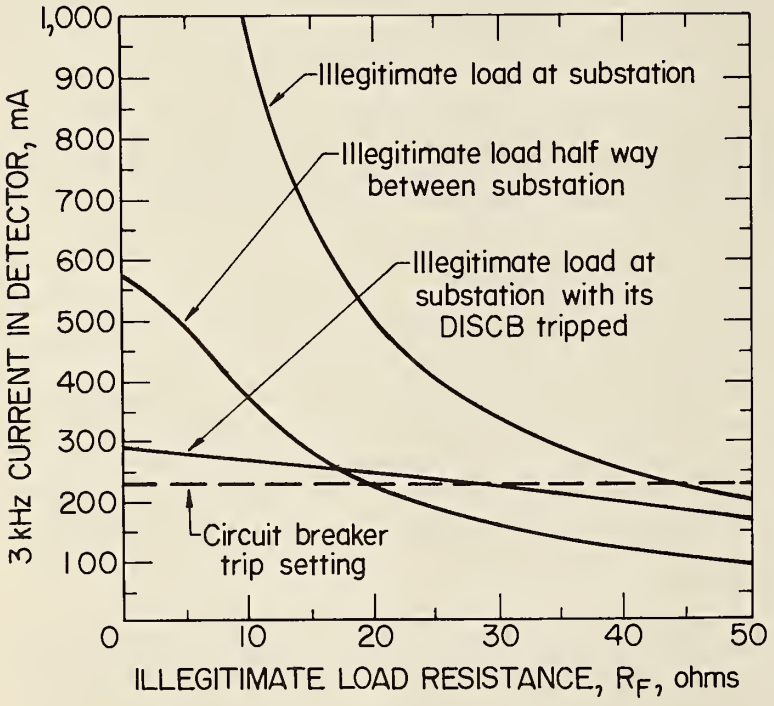

FIGURE 3. - Illustrating current through DISCB for different illegitimate loads – 1 mile between substations.

SENSITIVITY TO LEGITIMATE LOADS

Legitimate loads connected across the trolley will draw some 3 kHz current and thus bias the discriminating circuit breaker toward its trip level and make it more sensitive to illegitimate loads. However, it is considered that by insuring the total legitimate loading is greater than 100 ohms, sufficient freedom from spurious tripping can be obtained.

COMPONENTS OF THE DISCRIMINATING CIRCUIT BREAKER SYSTEM

A number of component equipments are required in the complete discrimination circuit breaker system. They are briefly identified and described as follows:

System Master Oscillator

One of these units would be required for the protection of a complete trolley wire system. The unit shown in figure 4 is housed in an aluminum enclosure 12 inches by 10 inches by 5 inches and weighs 13 pounds. It provides a nominal output of 8-volts, 3,000 Hz ±0.1 pct, which is used to activate the power amplifiers. Other features of the master oscillator include the following:

1. Input voltage 180 to 300 volts dc, or 100 to 140 volts ac.

2. Power ON light.

FIGURE 4. - Master oscillator unit.

3. Steady output voltage light that indicates output is available. This same light is caused to flash if the output is unacceptably low.

4. Meter to read magnitude of output voltage.

Substation Power Amplifier

A power amplifier capable of maintaining an output of 10 volts, 3 kHz is required at each dc substation. The units vary in size, depending on the substation characteristics. For a 300-kW substation, the amplifier is capable of about 18 amperes output, and a prototype unit shown in figure 5 is housed in an aluminum box 20 inches by 12 inches by 6 inches and weighs 43 pounds. When operated from the trolley wire voltage, a regulated dc power supply is used to supply power to the amplifier and this is also shown in the figure.

A signal to synchronize the power amplifier is obtained from a two-wire cable connected to the master oscillator. Because of possible amplitude and phase changes that may be caused by variation in the cable and substation characteristics, each power amplifier is equipped with independent amplitude and phase controls, which are adjusted at installation. These controls make it possible to minimize any 3-kHz circulating currents that otherwise could cause spurious tripping of the detector system

Discriminating Circuit Breaker Detector (DISCB)

One DISCB detector unit is required for each dc power circuit breaker. Typically this would mean two units at each substation--one to control the inby and one to control the outby. The 3-kHz current in the trolley wire is sensed by an air cored current transformer that feeds a signal to the DISCB detector. When the signal exceeds a certain level corresponding to an illegitimate load of 20 ohms or less, the DISCB detector provides an output of adequate power to operate a circuit breaker shunt trip coil. To avoid spurious tripping, a variable and adjustable time delay characteristic is obtained in the DISCB controls. For example, a 5-ohm fault causes tripping in about 0.4 sec, whereas a 15-ohm fault takes about 0.8 sec. Provision is

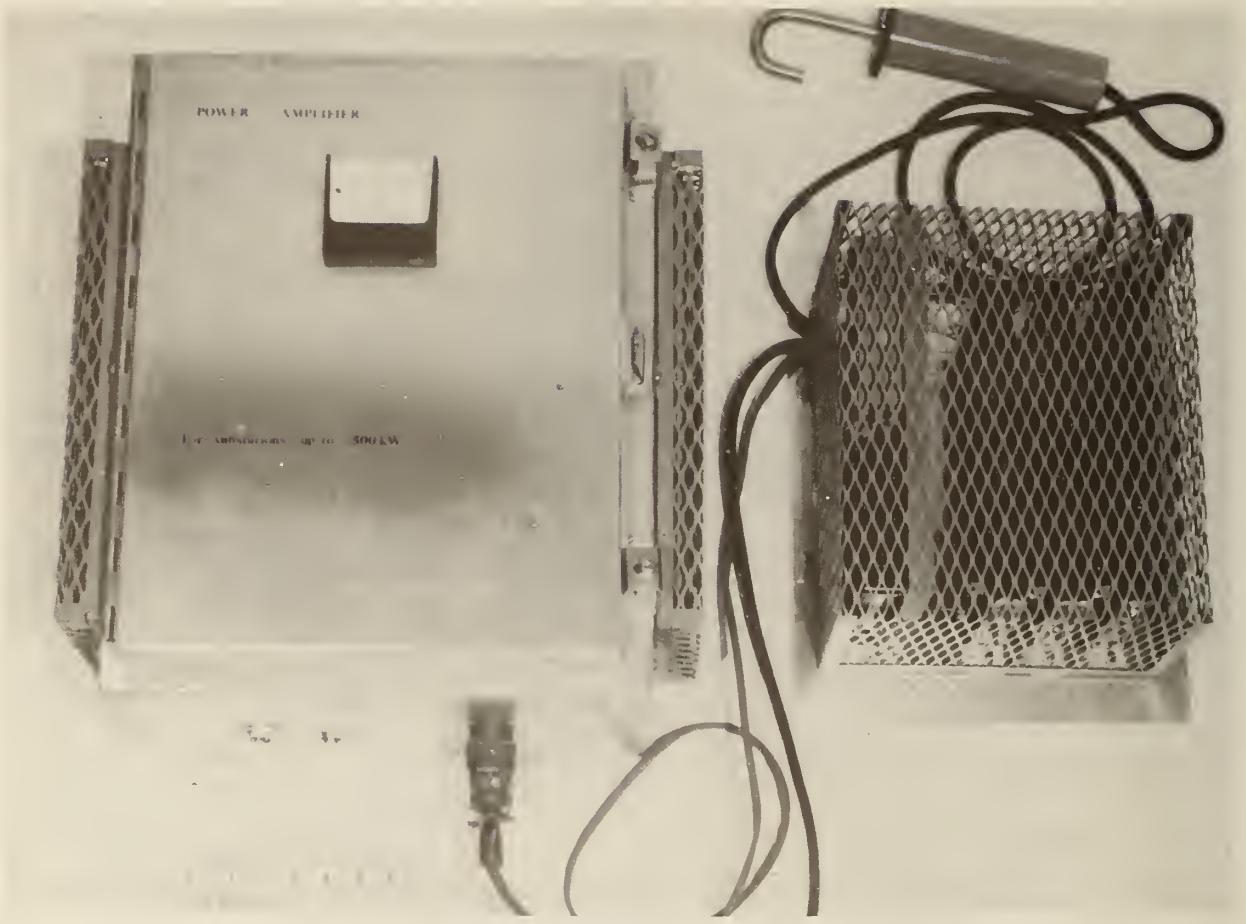

FIGURE 5. - Power amplifier unit.

made to recognize and cause tripping for an intermittent arcing type of fault of average value of 20 ohms or less.

A prototype unit is shown in figure 6. The unit size is 12 inches by 10 inches by 5 inches and weighs 12 pounds. Other features of the DISCB include the following:

1. Power supply obtained directly from the trolley wire.

2. A 3-kHz ammeter to record the trolley wire 3-kHz current.

3. A "detector ON" green light to indicate that the unit is energized.

4. A "trip ON" light to indicate than an illegitimate load has been detected.

5. A "push to test" button that, in operation, raises the DISCB sensitivity and enables the detector to sense its own power supply as an illegitimate load. Thus the DISCB detector unit can be routinely checked. In this

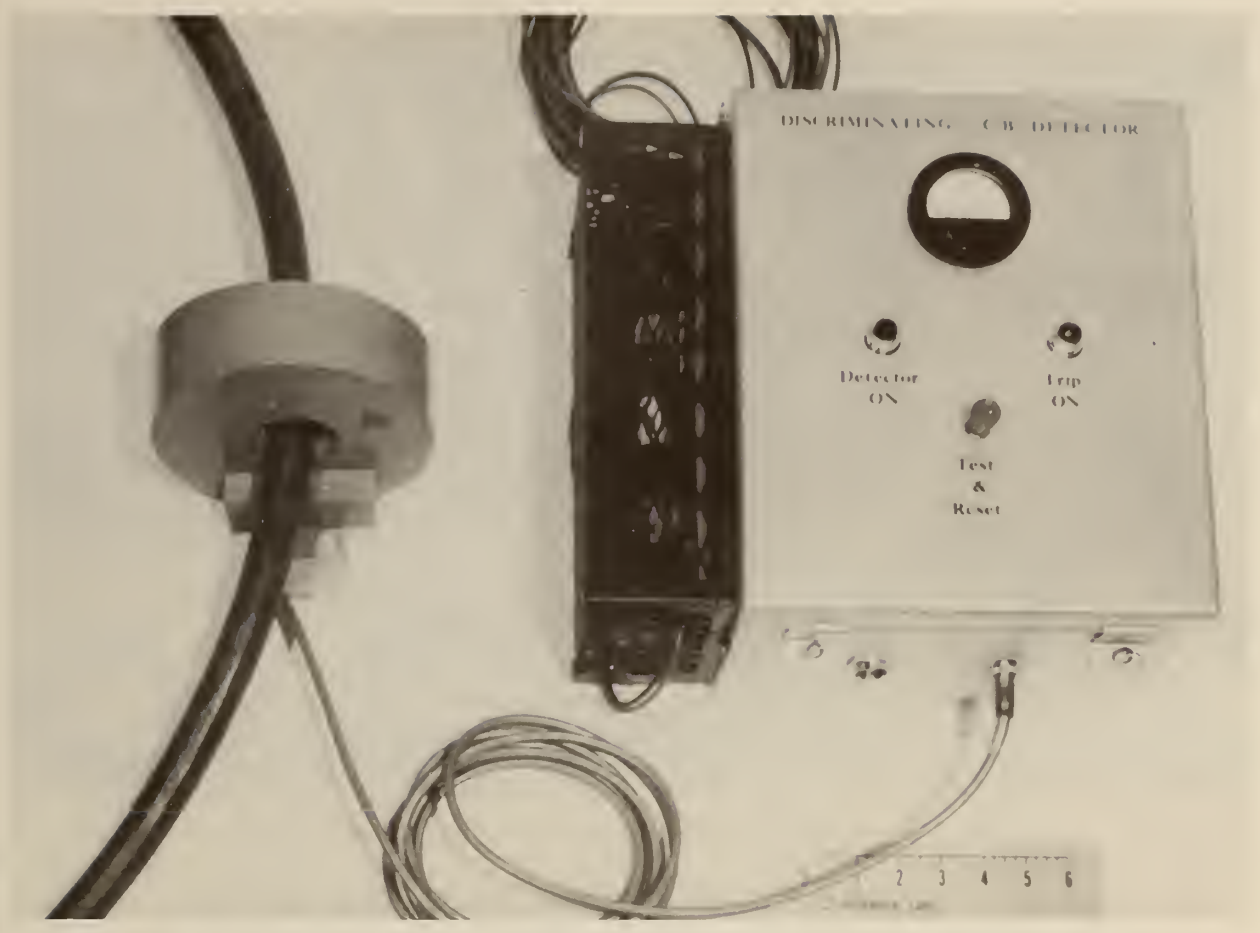

FIGURE 6. - Discriminating circuit breaker detector (DISCB).

test position, the output signal, which would cause the power circuit breaker shunt trip to operate, is momentarily disabled.

Active Impedance Multiplier and Power Supply

One of these units is required for each dc load in excess of about 35 hp. The unit is currently the subject of a patent application and will not be described in detail. Basically, it represents an electronic means for raising the effective 3-kHz impedance of large haulage motors. For a 600-hp locomotive, the unit requires a power supply 15 inches by 13 inches by 5 inches weighing 14 pounds. The controls are in a box 14 inches by 12 inches by 6 inches weighing 20 pounds. All the items associated with a 600-hp unit are shown in figure 7.

Static Filters for Small Loads

A variety of low-power loads may be connected to the trolley wire, and the impedance at 3 kHz is raised to between 500 and 1,000 ohms by means of series connected filter chokes. Typical of these filters are chokes weighing 5 pounds and 69 pounds for motors rated at 1 hp and 10 hp, respectively.

FIGURE 7. - An 800-hp active impedance multiplier and controls.

Tuned Air Cored Current Transformer

An air cored current transformer is used to detect 3-kHz currents for the discriminating circuit breaker detector unit and also the active impedance multiplier. The core consists of a toroidal Micarta annulus 5 inches OD by 3 inches ID by 1 inch high. When wound, there is a clearance hole of at least 2 inches through the center of the transformer through which the feeder wire is passed. A similar but larger unit with about a 3-inch internal diameter open is used with the largest locomotive and cables.

SYSTEM TEST RESULTS

In the development of the complete discriminating circuit breaker system, it has been necessary to conduct certain fundamental measurements to define the prototype equipment design parameters. Highlights of these tests are reviewed here.

1. Prototypes of all the various types of equipment were connected to the appropriate power supplies and left below ground in an operating coal mine for at least 6 months to insure that current and voltage transients existing on the trolley wire would not cause damage to the units. No problems were encountered.

2. A prototype active impedance multiplier was found to perform as expected on a 44-ton, 600-hp locomotive and raised the effective impedance at 3 kHz from 3.2 ohms to 100 ohms. Various static filters for pump loads ranging from 0.5 to 10 hp have operated satisfactorily.

3. A verification of the trolley wire parameters in one of the selected test sites was made at the Renton mine on July 27, 1974, when a 3-kHz power amplifier design was installed at a 300-kW rectifier substation. By applying 20 ohms and 10 ohms resistance loads at various points along the track and measuring the resulting 3-kHz current, the impedance of the trolley wire system was found to have an impedance of about 35 ohms per mile as anticipated.

Equipment was installed at a second test site at the Cambria No. 33 mine on December 6, 1974, and in this case a 2,700-foot dead end section was used for tests in conjunction with different trolley wire loads. A sketch of the test arrangement is given in figure 8.

Some fundamental system tests were carried out in this initial test arrangement and the results were very satisfactory. An 8-ohm test resistor used to simulate an illegitimate load at various points along the track caused the DISCB detector to operate; so also did different levels of arc currents, which were drawn from the trolley wire. The memory effect of the DISCB detector was found to operate satisfactorily so that short duration intermittent arcs were properly detected and caused the circuit breaker detector to trip.

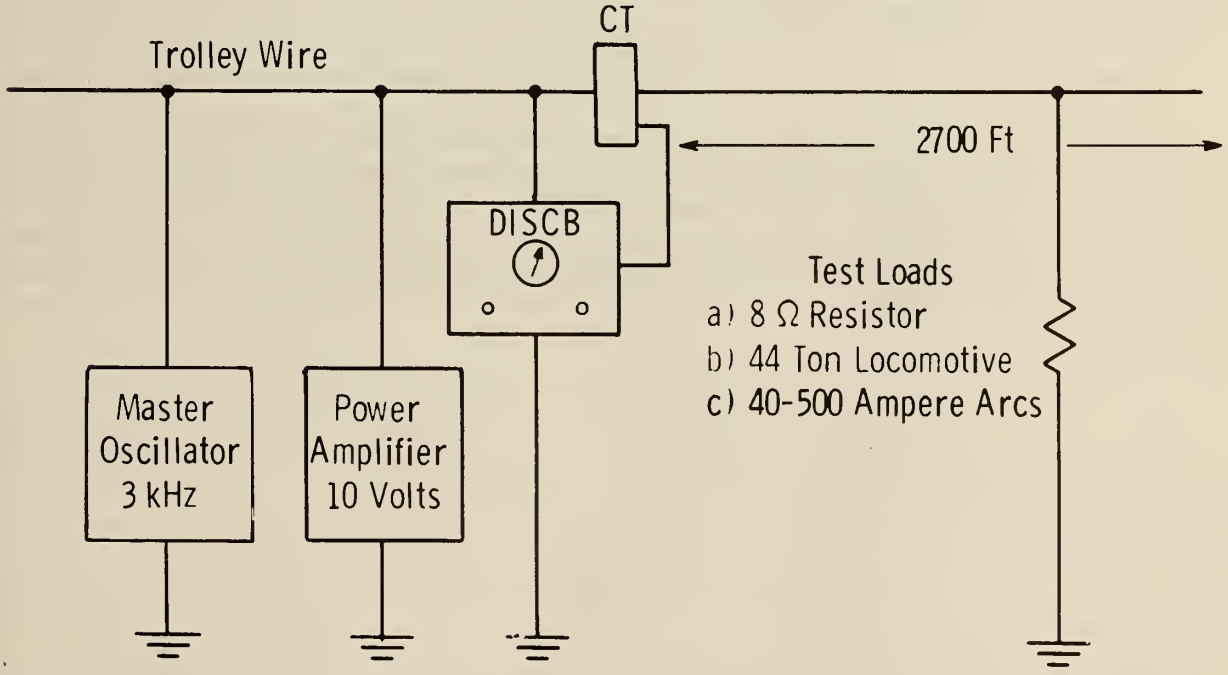

FIGURE 8. - Illustrating test arrangement for initial test at Cambria No. 33 coal mine.

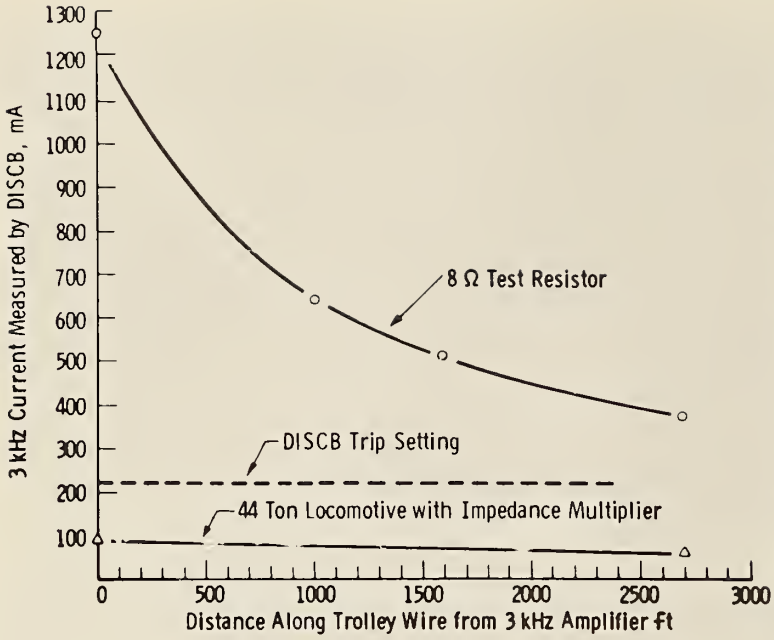

FIGURE 9. - Tests on discriminating circuit breaker at Cambria No. 33 coal mine.

A 44-ton locomotive with an active impedance multiplier installed was able to traverse the test section without causing the DISCB to trip. So also did a 13-ton locomotive with a smaller unit attached. During tests with the locomotives, no discernible transients were recorded on the DISCB detector ammeter despite frequent arcing of the dc current at the trolley pole and rails. This feature was especially gratifying and indicates that spurious tripping of the detector will not be caused by normal arcing, which occurs at the trolley pole connection. The pushbutton, which is installed on the active impedance multiplier mounted on the locomotive, was found to operate properly, and with the pushbutton depressed, the DISCB could be caused to trip. Some of these results are highlighted in figure 9.

CONCLUSIONS

A system for protecting the trolley and feeder wire of a coal mine electrical system has been devised and is currently being installed in one mile test sections of two operating coal mines. Component equipments of the system have been tested underground and found capable of satisfactory operation in the coal mine environment. System tests have confirmed the validity of the operating concept, and work is proceeding towards detailed trials and evaluation.

INTERMACHINE ARCING AND EVALUATION OF ARC SUPPRESSION METHODS

by

R. A. Wolf,[1] E. K. Stanek,[2] and P. Kantabutra[3]

ABSTRACT

This paper summarizes the cause and effect of induced voltages in multiple conductor cables supplying alternating current power to equipment in underground coal mines. The investigation of this phenomenon revealed that the electrical energy produced by the resultant electric arcing between the frames of mobile electric face equipment was of a sufficient magnitude to ignite explosive methane-air mixtures. The results of laboratory tests and field tests made between equipment frames during actual operation in numerous coal mines are discussed. Several methods of eliminating or suppressing the induced voltages to nonincendive levels are also described.

It is the purpose of this paper to convey to the mining industry a knowledge of this problem and to recommend methods of eliminating or reducing these induced voltages or arcing currents to safe levels.

INTRODUCTION

The implementing regulations as set forth in Title 30, Code of Federal Regulations, Part 75.906, specify that all low- and medium-voltage trailing cables for ac mobile equipment shall contain one or more ground conductors having a cross-sectional area of not less than one-half that of the power conductor and have an insulated conductor for the ground continuity check circuit. Compliance with this provision could not be achieved by the mine operators because available cables did not meet the specified requirements. The demand for a cable that would meet the specified requirements prompted the cable industry to convert the commonly used three-conductor type G round and flat cables to type G-GC by insulating one of the grounding conductors and increasing the cross-sectional area of the remaining ground conductor(s).

In March 1971, mining companies started replacing trailing cables on ac mining equipment with type G-GC cables as they became available and simultaneously began monitoring the cable grounding conductors. The observance of sparks between equipment frames was noted thereafter by machine operators and the occurrence was reported to the Mining Enforcement and Safety Administration (MESA). During an investigation of this problem, visible sparking was evident whenever contact was made between an ac continuous mining machine and a shuttle car, the frames of which were connected to a common ground. Following exhaustive tests, which disclosed no irregularities in the

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mining equipment or electrical supply system, it was concluded that this sparking was caused by voltage being induced in the grounding conductors of the continuous mining machine trailing cable by the load currents in the power conductors because of the cable asymmetry. In a balanced or symmetrical cable such as a type G round cable, the voltage induced in the ground wires will be zero, provided the ground wires are connected at both ends and the power system is balanced. It was suspected that the energy released by the arc was capable of igniting explosive methane-air mixtures. Subsequent tests conducted at the surface facilities of several coal mines confirmed the initial theory that the energy released by the arc was incendive. In this series of tests the incendivity of the energy arc was determined with a Physikalisch-Technische Bundesanstalt (PTB) spark apparatus described elsewhere in this paper.

Quantitative measurements of the voltages generated by various cable conductor arrangements--that is, open ground conductor(s), transpositions, etc.--were also made at this time. Induced voltages of 9 to 10 volts generated currents of approximately 10 amperes in the ground circuits during motor startup. In these tests, starting currents as high as 2,500 amperes were measured in the phase conductors. The arcs produced by these induced voltages were highly incendive. The cable was a 500-foot 4/0 AWG type G-GC. This latter revelation prompted MESA to impose a moratorium on ground monitoring of ac face equipment trailing cables on March 23, 1971, pending further investigation of this problem. An extensive program to determine the degree of hazard resulting from induced voltages in trailing cables under a wide variety of operating modes with respect to power demand, interaction between ac machines, trailing cable length and type, conductor size, etc., was conducted at the Westinghouse Electric Corp., high-voltage laboratory and in various coal mines.

A review of the conditions associated with this phenomenon indicates that the problem increases with the length of the trailing cable, the power demand of the machine, and asymmetrical geometry of the cable conductors. The presence of the ground check wire in the cable aggravates the problem because of the physical asymmetry it introduces into the cable configuration.

The potential methods for suppressing arcs due to induced neutral voltages include cable transposition, the use of symmetrical cables, the use of diodes and the use of saturable reactors. Each of these will be discussed in detail later.

The requirements for an acceptable arc suppression device include the following:

1. High impedance to induced currents.

2. Low impedance to fault currents.

3. High current carrying capabilities in the event of simultaneous phase to neutral faults.

4. Fail short mode of failure.

CABLE MODELS

An adequate cable model is needed in order to understand the phenomenon of induced voltages and current and to then evaluate means of suppressing the induced current that leads to the arcs. One of the simplest means of getting such a cable model in terms of self and mutual impedance is by use of a digital computer program developed at Purdue University called TRANS 3 (2)[4] This program can produce the parameters of virtually any type of cable used in a coal mine for distribution of power, remote control of equipment, or for communications. This program is available from George Conroy of the Pittsburgh Mining and Safety Research Center.

Without resorting to complex mathematics, it is of interest to see what factors influence cable induced voltages and currents. Using a method of analysis similar to that found in the cable parameter program, TRANS 3, it can be shown that the induced neutral voltage of a cable is

$$V = KLI_{\phi}, \tag{1}$$

where V = induced voltage (volts),

K = constant for a particular type, size, and condition, of a given cable (volts/amperes foot),

L = cable length (feet),

and I_{ϕ} = phase current (amperes).

This relationship is verified by test data described later in this paper.

The induced current is similarly found to be

$$I_i = K'I_{\phi} \tag{2}$$

where I_i = induced current (amperes),

and K' = another constant that depends on the cable type, size, and condition.

The reason that the induced current is independent of cable length is that the impedance is also proportional to length, and the ratio of induced voltage to impedance doesn't contain this term.

Generally speaking, the constants K and K' are larger for cables in which the neutral conductors are not symmetrical with respect to the phase conductors. Thus, K and K' are large for all flat conductors, and they are theoretically zero for intact round cables of type G or G-GC special. In practice, there is sufficient lack of symmetry even in these cables to produce some evidence of induced voltages and currents (3).

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[4] Underlined numbers in parentheses refer to items in the list of references at the end of this chapter.

Clearly, since one cannot limit phase currents or cable lengths, the only effective means of reducing arc currents are involved with changing K'.

DESCRIPTION AND RESULTS OF WESTINGHOUSE LABORATORY TESTS

The Approval and Testing Group of the Mining Enforcement and Safety Administration initiated tests at the Westinghouse Electric Corp. high-voltage test laboratory, East Pittsburgh, Pa., to determine the relation between voltages induced on the frames of mining machines and load current, cable length, cable geometry, and other factors. The minimum incendive currents generated by the induced voltages were also determined during these tests.

The tests were conducted on a test setup that included two 40-volt, three-phase, motor generator sets, one 425-hp and one 125-hp rating. These motors could be started singly or simultaneously in parallel so that load currents could be continuously varied from 60 amperes to 2,250 amperes. The test cables, up to 1,000 feet in length, were used to supply power to these motors.

The frame of a 75-hp, 250-volt, direct-current motor generator set was used as a substitute for a second machine. This motor generator was connected to the dc power center by an 800-foot No. 2 flat type G cable with a No. 4 ground conductor. The grounds of both cables were connected at the power center as shown in figure 1.

The load current in the ac power cables, the induced voltage between the frames of the ac machines and dc machines, and the current between the two machines were measured by a 12-channel CEC type 5-124P4-18 recording galvanometer.

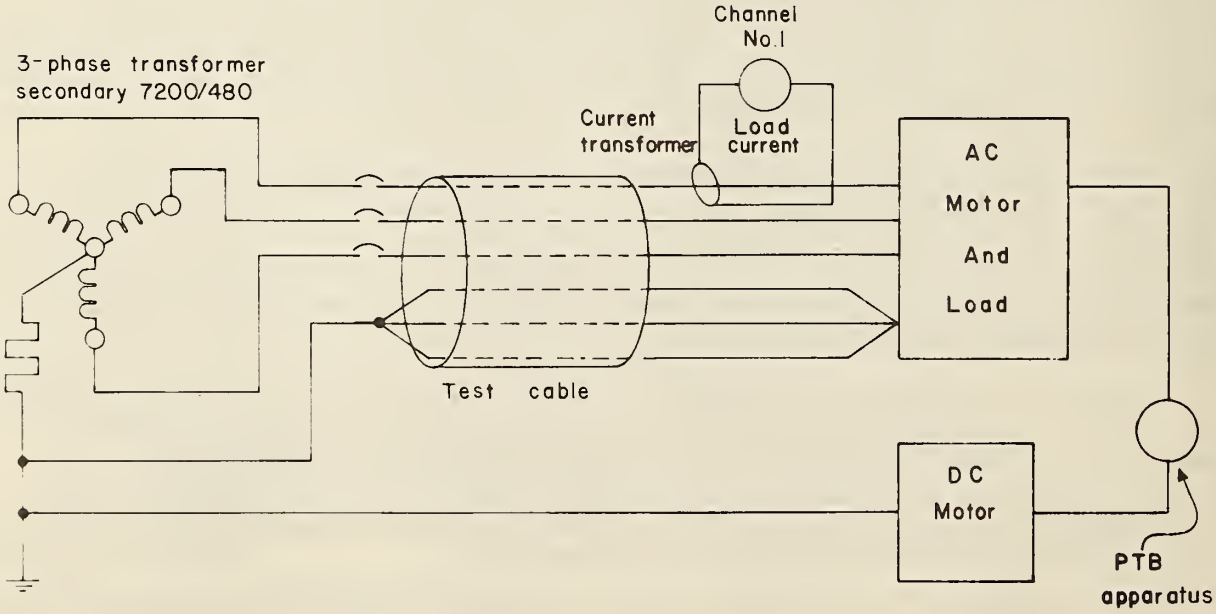

FIGURE 1. - Test setup at Westinghouse high-voltage laboratory.

The motor frames were connected through the Mining Enforcement and Safety Administration PTB spark apparatus so that the incendivity of the sparks could be assessed. This apparatus is similar in design to the Standard German Breakflash apparatus described in Verbund Deutscher Electrotechnisher (VDE) 0170/0171 d/2.65. The electrode system of the apparatus consists of two counter-rotating disks driven by an induction motor through a gear reduction train. The upper disk, slightly larger than the lower slotted disk, has a small instrument chuck attached to each corner to hold four 0.01-in-diam by 11-mm-long tungsten wires. The distance between the electrode holder and the cadmium disk is 10 mm, and the free length of the tungsten wire is 11 mm. Therefore, as the disks rotate, the tungsten wires scrape the cadmium disk and make and break the circuit. The motor speed and gear ratio used in these tests make and break the circuit about 400 to 500 times per minute.

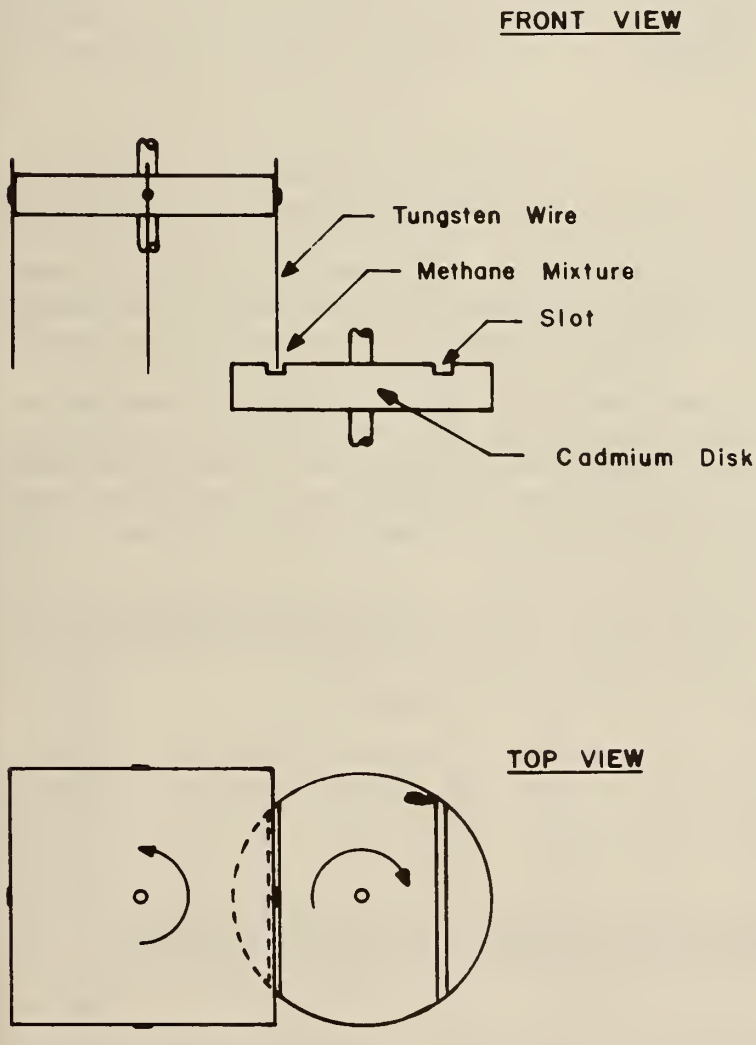

FIGURE 2. - PTB chamber.

The electrode system is mounted on top of a plexiglass base plate with the motor and gear train mounted below the base plate. A glass dome of approximately 1 liter capacity encloses the electrode system and the gas mixture. The dome is held in place by a brass-ring fitting over the flanges of the dome, and the system is sealed by an 0 ring. The motor control, gas flow system, and gas cutoff valves are also mounted below the base plate.

The explosive mixture was supplied to the chamber continuously by a flow system from two high-pressure tanks of methane and air. The methane concentration was measured continually by an MSA Model 300 lira infrared analyzer.

All electrical connections were made outside of the explosion chamber. The frames of the ac motor generators were connected through the shaft of the revolving disk that held the tungsten wires. The cadmium disk was then connected

through a shunt for current measurement to the frame of the dc motor. Figure 2 shows the PTB apparatus.

The usual test sequence consisted of the following:

The selected cable was connected to the ac motors as designated and all instrumentation checked. The PTB apparatus was charged with the proper gas mixture (7.8 to 8.6 pct methane by volume and air) and then the motors were started. The line current in the cable and the voltage and current between the machine frames were recorded, and also, the incendivity of the spark was determined. The starting or inrush currents were generally the highest obtained, and if they were incendive, the procedure was repeated using lower load currents until a load current was reached at which the induced voltage and current were not incendive. After the nonincendive current level was determined, the cable configuration was changed by transposing power or ground conductors, opening one or more ground or ground check conductors, or connecting ground check conductors as grounds until all possible cable configurations were tested. This procedure was followed for the eight cables that were investigated.

The test results were analyzed by the Electrical Engineering Department of West Virginia University under Federal Bureau of Mines Contract G0122088. The complete statistical evaluation of the test data is given in the final report for that contract. These results are too voluminous to reproduce here, but a sample of them is given in table 1. Table 1 also includes a list showing the connections of the various ground conductors or ground check conductors. The three possible ground or ground check configurations tested were connected to ground (symbol 0), open (symbol X), or connected to a monitoring circuit (symbol M). As far as induced voltages and currents are concerned, the open and monitor configurations are equivalent since the circuit impedance in either case is large compared with that of a direct ground to frame connection. The table also shows whether the induced current is incendive or nonincendive in methane-air mixtures.

TABLE 1. - Three conductors 4/0 type G with axial ground check wire

Cable length, feet	I_L, amps	V_I, volts	I_I, amps	G_1[1]	G_{21}[1]	G_3[1]	Incendive arc
810	2,000	0.6	0.3	0	0	0	No
810	1,950	14.5	18.0	0	0	X	Yes
810	180	1.5	1.9	0	0	X	Yes
810	135	1.4	1.8	0	0	X	No
810	1,750	25.0	28.0	0	X	X	Yes
810	100	1.8	2.0	0	X	X	Yes
810	75	1.4	1.5	0	X	X	No
WITH TRANSPOSITION (THREE EQUAL SECTIONS) OF POWER CONDUCTORS							
810	1,960	0.3	0.3	0	0	0	No
810	1,960	.3	.3	0	0	X	No
810	1,960	.3	.3	0	X	X	No

[1]0 Connected to ground.
X Open.
M Connected to a monitoring circuit.

The results of these tests show that the voltage induced on the frame of a machine connected to the ground wires in a cable is proportional to the current in the phase conductors (load current) and the length of the cable for any given cable configuration.

The test results show that whenever two machines grounded at the same point come in contact, the voltage induced on the frame of either machine will generate a current that is limited only by the impedance of the ground loop. This can be expressed as

$$I = \frac{E}{Z} = K\frac{I_L L}{Z}. \quad (3)$$

where Z is the ac impedance,

$$Z = \sqrt{R^2 + (X_L - X_C)^2}, \quad (4)$$

R = circuit resistance,

X_L = circuit inductive reactance,

and X_C = circuit capacitive reactance.

In the circuits considered, X_C, capacitive reactance, is negligible at 60 Hz. Also, in all of the cables tested, the resistive component contributed the largest part of the total circuit impedance.

The test results also show that the minimum ignition current for the various circuit configurations ranged from 1.2 amperes to 1.6 amperes depending on the various cable parameters. This agrees with independently obtained data from other tests using the PTB apparatus. Calculated inductance of the various ground circuits vary slightly but are approximately 0.5 mH. The stored energy in a 0.5-mH, 1.5-ampere circuit is approximately 0.5 mj while the minimum ignition energy of an inductive circuit in methane-air atmospheres is approximately 0.5 mj.

DISCUSSION AND RESULTS OF FIELD TESTS

Field tests were conducted in coal mines in Kentucky, Ohio, Pennsylvania, Virginia, and West Virginia following the laboratory investigation. The primary objective of these tests was to determine the extent and gravity of induced voltages in power cables supplying ac power to electric face equipment during actual mining operations and to also test several methods of suppressing the current resulting from these induced voltages. Continuous miners, boring machines, roof-bolting machines, shuttle cars, and loading machines, equipped with trailing cables of varying lengths, sizes, and types, were investigated. The current between machine frames and between the machine frames and earth through a steel roof bolt were determined by measuring the voltage across a 0.1-ohm shunt with a Du Pont model 101 Blasters[5] multimeter

[5]Reference to specific products does not imply endorsement by the Bureau of Mines.

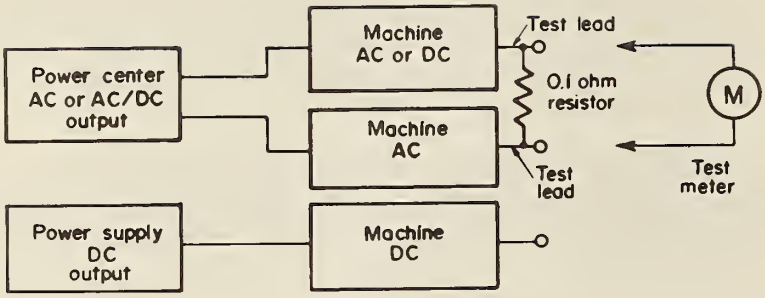

FIGURE 3. - Block diagram showing application of the test device to intermachine arc testing.

FIGURE 4. - DuPont model 101 Blasters multimeter.

using the 150-mV ac scale as described and shown in figures 3-4. This meter was selected because the input characteristics of the instrument are specially designed to accurately measure ac voltages in the range from 0 to 150 mV. The sensitivity of the meter in this range is approximately 750 ohms per volt. Usually tests were made between the frames of a continuous mining machine and a shuttle car, although loading machines or roof bolting machines were occasionally substituted for the shuttle car. Nearly every machine combination exhibited an indication of induced voltage, particularly when the motors were started or heavily loaded. In most cases, the voltage measured when operating the continuous mining machines was more than 100 mV (1 ampere). This was even noted when new type G round trailing cables, in apparently excellent condition with all ground conductors connected to the machine frame and grounding system, were used on the continuous mining machines. The preceding tests were conducted with the cable ground conductors and/or ground check wire connected together. Measurements made between the machine frames and earth through roof bolts did not indicate any voltage on motor startup or during mining operations. Induced voltages also were not observed between the equipment frames if the grounding circuit of one of the machines was open. The tests also verified that the severity of induced voltages increased considerably whenever one or more ground conductors in the cable were opened. Even when the ground check wire was connected for the purpose of monitoring the grounding circuit or if the cable symmetry was destroyed in any way, the severity of induced voltages increased.

The most significant information derived from these tests was that the maximum severity of the induced voltages was approximately 10 to 11 volts when the large motors (300-hp maximum) on the continuous mining machines were started.

This is considerably less than the Westinghouse tests or West Virginia University (4) study predicted. However, the source impedance was low; consequently, the load currents were greater at the Westinghouse test facility than might be expected in commercial mining operations.

ARC SUPPRESSION DEVICES OR METHODS

Basically, there are four methods of solving the problem of induced voltages and the subsequent arcs that they cause. The remainder of this paper will discuss these devices and methods, listing the advantages and disadvantages of each. The four methods of reducing arc currents are the following:

1. Transposition of phase conductors.
2. Use of symmetrical cable types.
3. Use of diodes to suppress arc currents.
4. Use of saturable reactors to suppress arc currents.

CABLE TRANSPOSITION

The transposition of cables merely means to change the position of the phase conductors with respect to the individual neutral conductors at various positions along the length of the cable. Ideally, each phase conductor will occupy each position with respect to the neutral conductors for one third of the cable length. A little thought will reveal that this can be accomplished by cutting the cable twice and splicing it as shown schematically in figure 5. The concept of transposition is an old one, and it has been used for years by electric utilities to eliminate imbalances on overhead transmission lines.

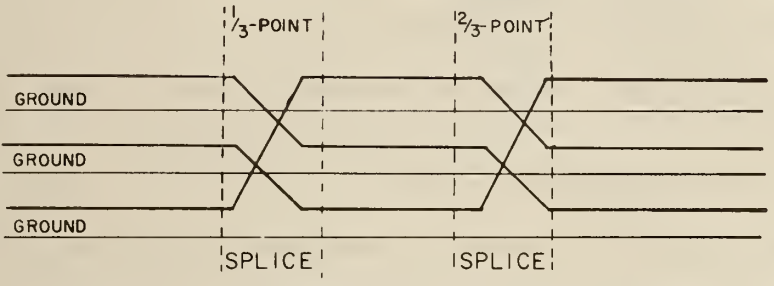

FIGURE 5. - Power conductor transpositions shown in three-conductor type G round cable.

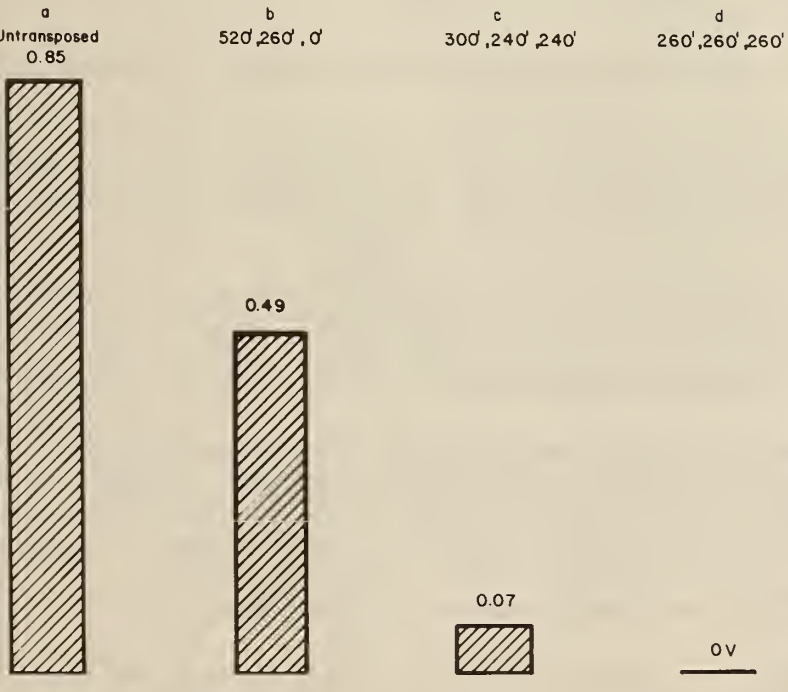

FIGURE 6. - Effectiveness of transposition when transposition sections are of different lengths.

The reason that transpositions eliminate the problem of induced voltages and therefore intermachine arcs is based on the manner in which voltages are induced in the neutral conductors by currents in the phase conductors. If a neutral conductor is located the same distance from all three phase conductors, the voltages induced by the three phase currents add up to zero vectorially. By

transposing the phase conductors so that each phase current occupies each position one-third of the cable length, one gets the same effect as placing the neutral conductor equidistant from the phase conductors.

It is of interest to see what happens when the transposition lengths are not all equal. This is of practical interest because as the cable is used it is common for damaged sections near the end to be cut off rather than spliced. Figure 6 illustrates by means of a bar graph the portion of induced voltage and arc current that results for various degrees of transposition imperfection. For the bar graphs, it is clear that even when the transposition lengths were rather far from equal that the technique still drastically reduced the induced voltage and arcing current. Transposition is effective even when the lengths of one or more segments are altered by 25 pct or more.

The advantages of cable transposition can be enumerated as follows:

1. Transposition is useful for all cable types.

2. For equal transposition lengths, it is theoretically 100 pct effective, and in practice, this value is approached.

3. No new cables nor special devices are needed.

4. Properly shielded cable gives the effect of continuous transposition.

The disadvantages of cable transposition are as follows:

1. It shortens cable life and physical strength.

2. It is difficult to maintain equal transposition lengths in actual practice.

3. It may be difficult to get and keep correct transposition due to the fact that maintenance personnel are accustomed to splicing like color conductors together.

4. There is no visual inspection that will reveal if correct transpositions are present.

EFFECT OF CABLE TYPES

It has already been mentioned that symmetrical cables theoretically exhibit no induced voltage or arcing current phenomena. In fact, however, a symmetrical cable that has been spooled has considerable distortion and is not truly symmetrical. Cables of this type still have measurable induced voltage and arcing current (3). The most often used cable types are shown in figure 7 and are grouped together as symmetrical and asymmetrical.

The only symmetrical cables in common use are the type G round and the type G-GC round special. The type G round has no insulated polot wire and as such is suitable for use only with pilotless ground monitors. The type G-GC

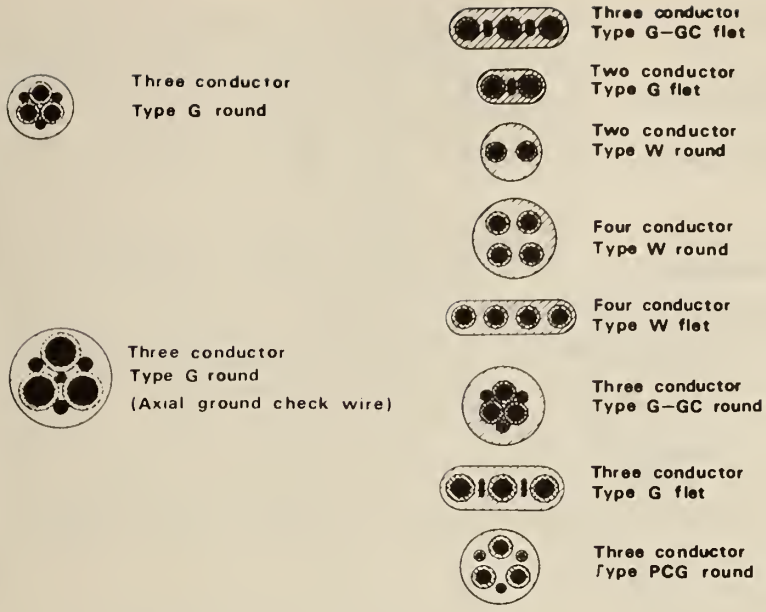

FIGURE 7. - Trailing cable types.

round special cable is suitable for use with either a pilot or pilotless monitor. It should be noted that any unbalanced loads in the power conductors or any defects in the power or ground conductors will alter the symmetry of the cable, and a resultant induced voltage will be impressed on the machine frame.

The degree of severity of induced voltages for each type of cable in figure 7 is illustrated in figure 8. In this figure each cable is a 4/0 cable with rated current flow (according to Schedule 2G) in its phase

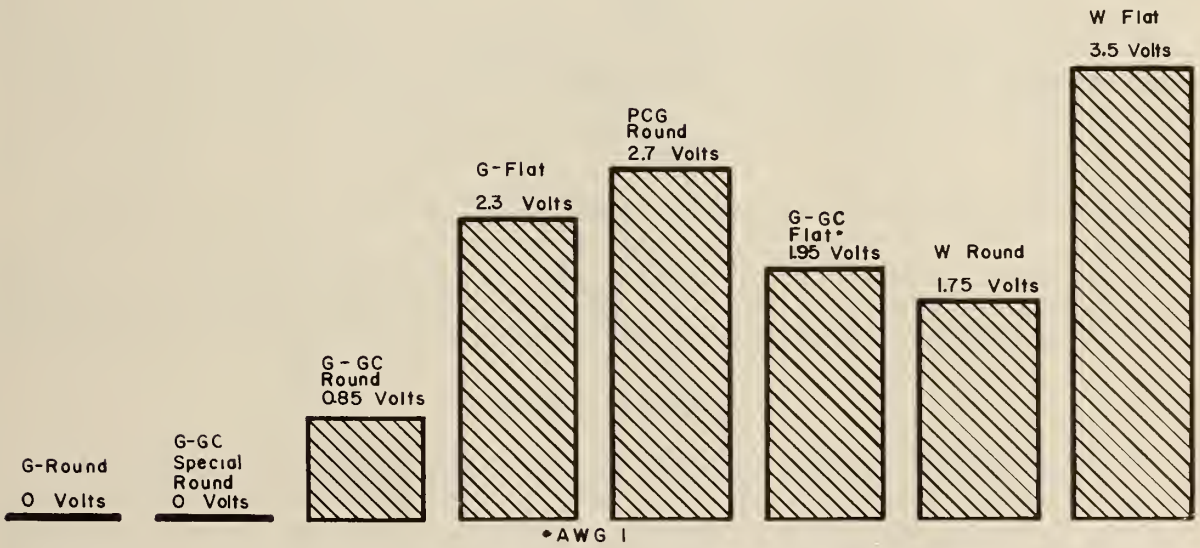

FIGURE 8. - Induced voltage for various types of three-phase trailing cable—size 4/0, 1,000 feet, with full load current.

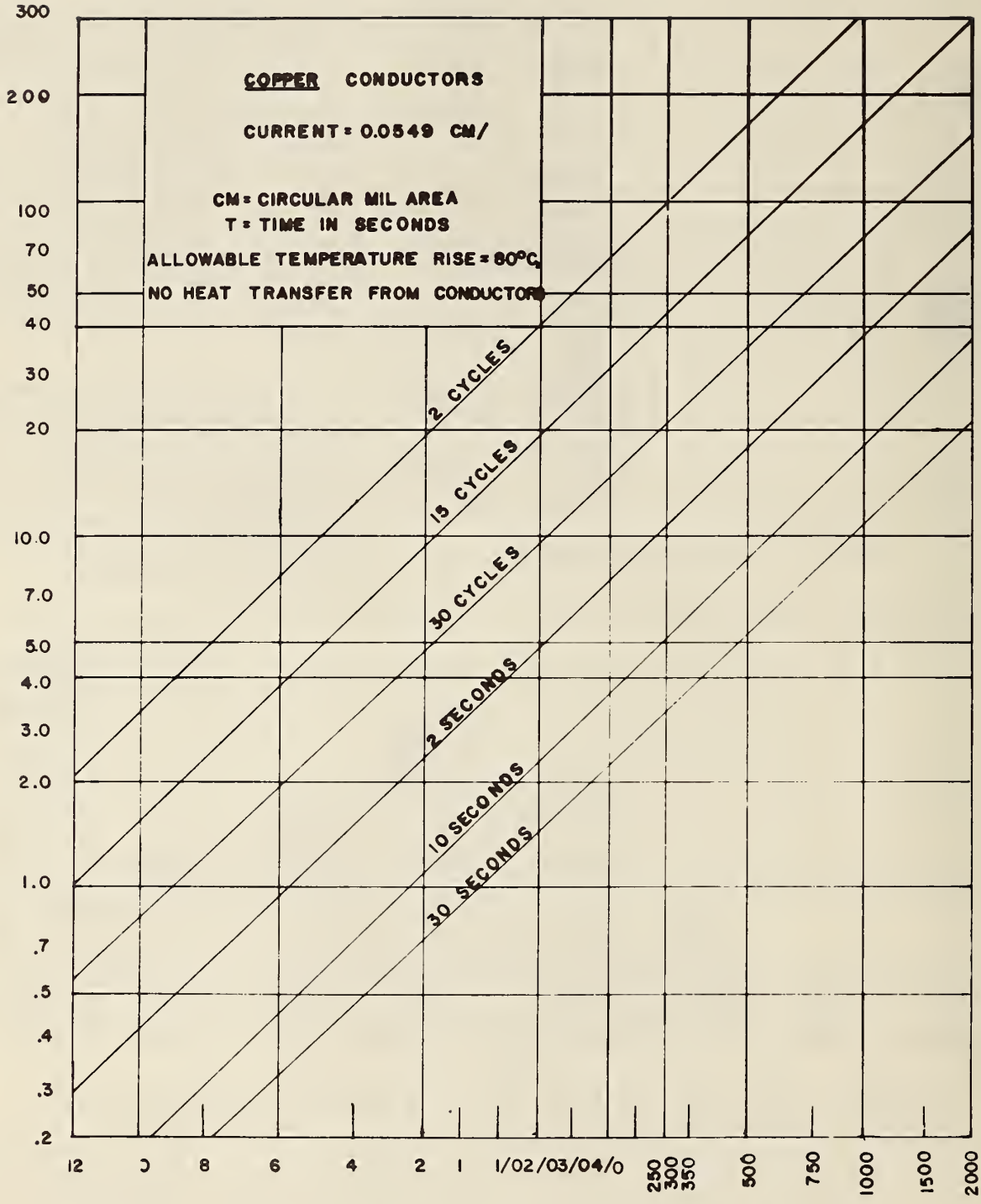

FIGURE 9. - Allowable short-circuit currents for insulated copper conductors.

conductors. The relative height of the bars in the graph represents the severity of the arcing current problem. Clearly, flat cables are more of a problem than round cables. However, it should be pointed out that the graphs are for completely intact cable neutrals. If one or more neutral conductors are broken in a round cable, the induced voltage and arcing current will be substantially larger.

The evaluation of the effect of cable type is by necessity somewhat qualitative because the state of the neutral conductors has a profound influence on the severity of the induced voltage-arcing current problem. Although the use of symmetrical cables appears to be a feasible long-term solution to the problem, in reality it is only if one monitors the continuity of individual neutral conductors. This can be done by either using redundant monitors or by the use of a monitor developed by West Virginia University for the Bureau of Mines called a negative-sequence ground conductor monitor (1). The problem of ground monitoring will not be discussed in detail here, except to say that monitoring of individual ground conductors is costly.

ARC SUPPRESSION DEVICES

The other approach to solving the problem of induced voltages and arcing currents is to insert a nonlinear impedance as opposed to trying to modify the cable performance. The basic idea is to provide a nonlinear impedance that has a high effective impedance at low values of voltage such as an induced voltage and a low effective impedance to higher voltages and currents that are present when a fault occurs. Two approaches to the problem are to use either a nonlinear resistor (a diode) or a nonlinear inductor (a saturable reactor). The nonlinear resistor will be considered first.

Any such device that is installed in the cable ground conductor for the purpose of suppressing intermachine arcing shall have a continuous current rating of 25 amperes or more and have a short circuit current capability equivalent to the cable ground conductor(s). The short-circuit current capabilities shall comply with the values as set forth in figure 9.

DIODE SUPPRESSION

The diodes used to suppress arcing currents must be able to carry alternating currents. This can be done by connecting diodes in parallel with their polarities reversed, but a more effective use of diodes is to connect them in a bridge arrangement as shown in figure 10. In this arrangement, the center diodes conduct at all times, and two of the outer diodes conduct every alternate half cycle. Thus, the effect of getting n diodes in series for currents of both polarities can be attained with n + 2 diodes instead of 2n diodes.

The type of diodes used will conduct about 1 ampere of current with a voltage drop of 0.6 volts. Since an incendive arc occurs with a current of around 1 ampere, if a sufficient number of diodes are used to limit the current to this value, the danger of explosion can be eliminated. Therefore, if the induced voltage is 6 volts, then 10 diodes in series will limit the

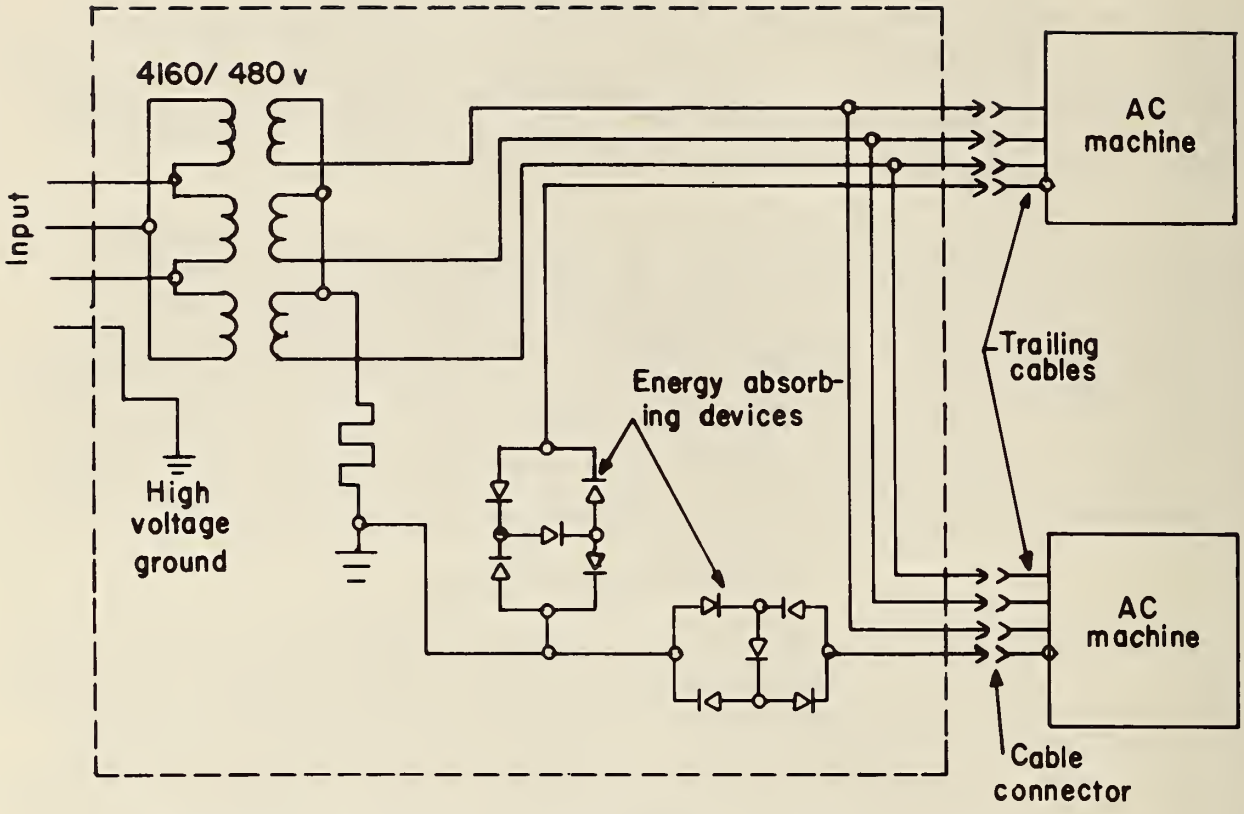

FIGURE 10. - Application of energy-absorbing devices in ac power center.

current to about 1 ampere. If a bridge arrangement is used, then a total of 12 diodes would be required.

Because a resistance grounded system is used, the line-to-neutral fault current is limited to less than 25 amperes (by law). It is possible to have simultaneous line-to-neutral faults on different phases at different points on a system. When this happens, the arc suppression diodes may be forced to carry full line-to-line short circuit current. This current will generally be several thousand amperes depending on the system configuration, device ratings, location of the faults, etc. It is not necessary that the diodes successfully carry this current without damage to their junction, but it is necessary that if the diodes fail they fail short as opposed to open. In all tests conducted by the Bureau of Mines and manufacturers to date, the diodes have always failed short. A comparison of actual and ideal diode characteristics are shown in figure 11.

The advantages of diodes are as follows:

1. They work for all cable types.

2. They can be effective even for cables that have broken neutral conductors.

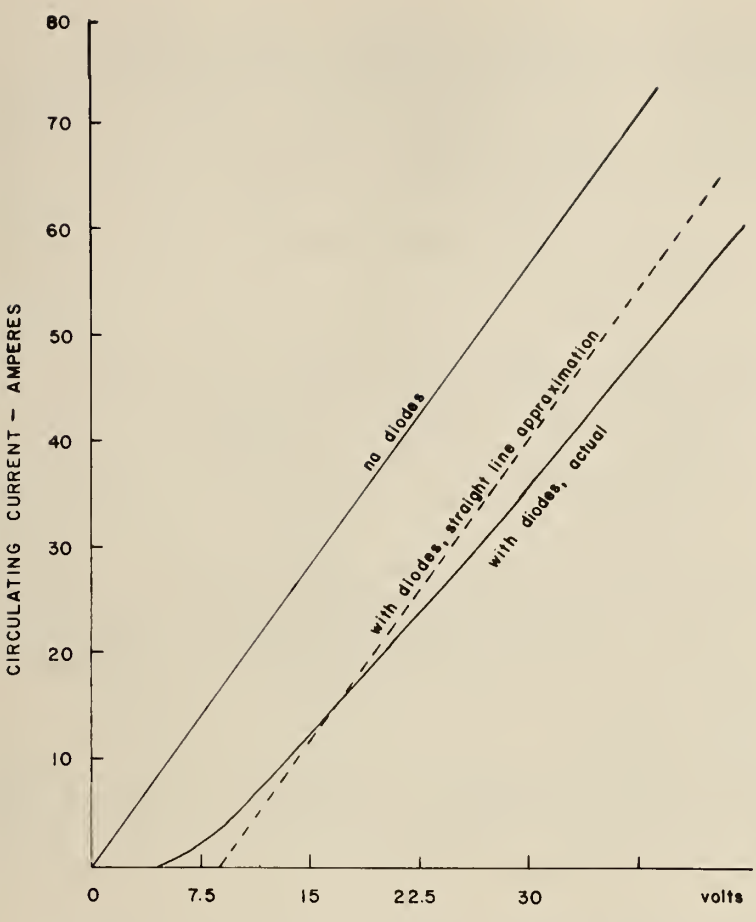

FIGURE 11. - Comparison of actual and ideal diode characteristics.

3. They are not prohibitive in cost.

4. They don't affect ground monitor performance.

The disadvantages of diodes are as follows:

1. They are ineffective if the junctions have been destroyed by high current.

2. Reasonable care must be exercised in chosing the number of diodes needed. It depends on the condition of the cable neutral.

3. They are never 100 pct effective.

The General Electric No. 0208A8292 machine arc suppressor (diode bridge), as shown digrammatically in figure 10 is capable of blocking approximately 2 volts, and additional units can be connected in series if higher induced voltages are encountered. The diode bridge is rated at 25 amperes continuous and 7,500 amperes ac symmetrical rms for 32 msec. These machine arc suppressors (MAS) were tested to failure by the manufacturer. In these tests, the diodes were subjected to currents of from 7,400 amperes for 2 cycles up to a maximum of 22,800 peak amperes (maximum test current available) for 2 cycles. In all tests, one or more diodes failed, but none failed open circuit. The higher test current is far in excess of the maximum fault current that could be expected during simultaneous grounds (double faults) on different phases at different points in a low voltage system. Even under the most severe fault conditions, the integrity of the ground circuit would be maintained. This device is acceptable for use in all common types of trailing cables.

A Motorola Semiconductor Inc. diode voltage limiting device (Bi-Lateral Stabistor) was designed for suppressing induced voltage up to 10 volts. This device was tried in field tests and effectively suppressed the induced voltages; however, present test data (table 2) indicate that this device is acceptable for use with a No. 8 or smaller size grounding conductor.

TABLE 2. - Preliminary test data for Motorola Semiconductor Products MRA70065 Bi-Lateral Stabistor assembly, July 10, 1974

	Specifications
Threshold turn-on voltage	6.5 volts nominal voltage drop measured with 1 ampere flowing through the device.
Continuous current rating	25 amperes ac rms. (Voltage drop 8.5 volts nominal at 25 amperes.)
Maximum nondestructive surge currents.....	7,000 amperes symmetrical ac rms for 3 cycles (50 msec) without failure. Device will failtto a short circuit in region of 8,000 to 9,000 amperes ac rms. Voltage drop 36 volts peak during surge.
Meltdown current.....	Device will not fail to an open circuit at 70,000 amperes ac rms symmetrical fault current for 3 cycles. (In prototype device tests run by private test labs, 2-0 copper connecting cables burned off at terminals but device remained a solid short.)
Mechanical.....	Approximately 6 inches by 6 inches by 6 inches over all.
Price.....	$425.
Delivery.....	Starting October 1, 1974.

NOTE.--Design to be connected in series with grounding conductors in trailing wire cables of high-powered mining machines to eliminate intermachine sparking.

SATURABLE REACTORS

As pointed out earlier, any nonlinear circuit element can be used to limit arcing current without affecting fault currents provided the device exhibits high impedance for low currents (arcing currents) and low impedance for high currents (fault currents). With this in mind, it is natural to try saturable reactors to suppress arcing currents. The saturable reactor has several advantages over diodes (nonlinear resistance). The primary advantage is that there is no junction of semiconducting materials that is subject to damage by heat, voltage spikes, or excess rate of rise of current. A saturable reactor is nothing more than an iron core inductor that has high incremental impedance or inductance up to the point where the flux in the core saturates the iron. When the iron becomes saturated, the incremental ampere-turns produce flux at the same rate as if the device had an air core. Since the relative permeability of iron is much greater than air, the inductance of the reactor is much less after saturation than before. This means that for small

voltages and currents, such as induced voltages and arcing currents, the saturable reactor will limit the current to a safe value and act as a linear device. For fault currents and voltages, the saturable reactor will operate in both the linear and nonlinear region. This means that the current will not be sinusodial. However, since the bulk of the operation is in the nonlinear region, the effective impedance will be low. This is necessary if the ground is to be effective in keeping machine frames at or below a voltage considered to be safe (40 volts for a prescribed period).

The selection of a saturable reactor characteristic that is suitable for suppression of arcing currents is somewhat similar to the selection of the number of diodes outlined previously. The primary information needed to chose a particular characteristic is the amount of induced voltage present. This can be found by well-known analytical techniques and test data.

Once the value of induced voltage is known, then a reactor should be chosen that will operate in its linear region for the value of induced voltage found and limit the arc current to one ampere or less. In addition, the reactor should saturate for a slightly higher voltage and have a minimum effective impedance in the saturated state to limit machine frame voltages during faults. These factors are demonstrated on the saturable reactor characteristic in figure 12.

Saturable reactors are subject to damage by the high currents that flow when simultaneous faults occur on separate phase at different locations. If the wire used to wind the core is not large enough, it can be fused by this large current. Of course, it is easier to design a wire to carry a large fault current than a p-n junction. If the wire is fused, the device must fall short, just as the diodes must, for the device to be safe.

Another potential problem with saturable reactors is that the reactor is an inductor and therefore it stores energy. This energy can cause the value of incendive current to be made lower. The decrease in the value of incendive current can be prevented by making the quality factor (ratio of inductive reactance to resistance) lower. This can be done by using higher resistance wire up to the point that the wire doesn't melt due to fault currents.

The advantages of saturable reactors as a means of suppressing arc currents are as follows:

1. They are applicable to all cable types.
2. They have no junction that can be damaged.
3. They are inexpensive.
4. They conduct in both directions.

The disadvantages of saturable reactors as a means of suppressing arc currents are as follows:

1. The energy stored in the saturable reactor may lower the minimum value of incendive current.
2. The wire used to wind the reactor can be destroyed by simultaneous line-to-neutral faults.

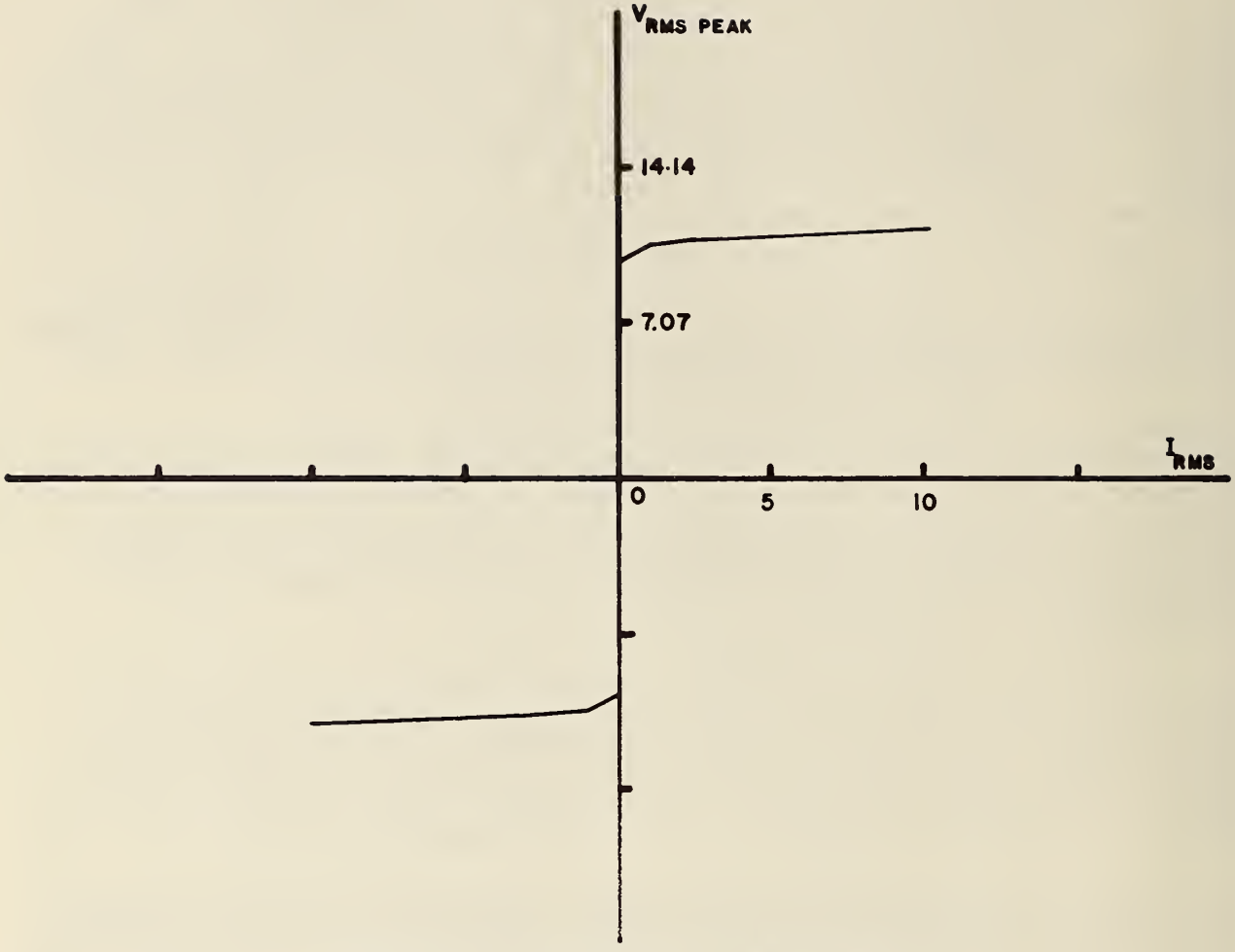

FIGURE 12. - Saturable reactor characteristic.

3. Saturable reactors produce voltage spikes under fault conditions.

4. Parallel reactors don't share current equally.

A saturable reactor device has been successfully tried at two mines. This device is essentially an inductance with high initial permeability and high inductance at low currents; however, high currents saturate the core, and consequently the inductance is very low. The current-voltage relation is shown in figure 12. The reactor used in these tests had been designed to saturate when 7.5 volts are across it; however, any desired voltage breakdown can be designed into the unit. Published data indicates that this reactor is acceptable for use with a No. 7 or smaller size ground conductor.

These devices are equally effective if installed between the machine frame and ground conductor or in the power center between the ground conductor and ground. However, it should be noted that when they are applied in the power center, it is absolutely essential that the grounding pin in metal

enclosed cable connectors or plugs be isolated from ground to prevent the device from being shorted out. In such cases, the metal plug should be connected to the receptable by a wire shunt. The voltage limiting effect of the voltage suppressors affected the performance of ground monitoring relays in several instances during these tests, and it was necessary to increase the check circuit voltage or replace the existing relay with a more sensitive one. Since each diode effectively drops 0.6 volt, an approximation of the number needed to suppress the induced current can be made by measuring the open circuit voltage between machine frames during the tests.

CONCLUSIONS

The phenomenon that produces induced voltages and intermachine arcing has been described. Both laboratory and field measurements of these quantities have been presented. Tabulated data resulting from these measurements have been introduced.

Four methods have been described for suppressing arc currents. Two methods involve eliminating the induced voltages, and two involve inserting nonlinear impedance to limit the arc current without preventing the flow of fault current. Eliminating induced voltage by either transposition or the use of symmetrical cables has a drawback; in field situations, there is little confidence that the transposition lengths will remain equal or that the cable neutrals will remain symmetrical. The use of nonlinear impedances to suppress arc currents, although not as completely effective as transpositions or symmetrical cables, is a more reliable method. The nonlinear elements can be relied on to limit arc currents and to carry fault currents. Diodes have the drawback that they can have their junctions destroyed by thermal or voltage stresses. However, field tests have shown these devices to fail short. Saturable reactors are more durable but may add to the problem of igniting air-methane mixtures because of the energy that they stored in their magnetic fields. Because of the requirements that arc suppression devices carry as much current as the ground conductor, the saturable reactor described can only be used with a No. 7 or smaller ground wire. Similarly, one diode described was acceptable for all available cable types; another is usable only for ground conductor sizes of No. 8 or smaller.

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GROUNDING AND GROUND CHECK MONITORS

by

Wils L. Cooley[1] and Ralph L. Rinehart[2]

ABSTRACT

This paper summarizes recent experiments with grounding systems. Problems and potential hazards related to in-mine grounding systems are discussed. The monitoring of trailing cable ground conductors and testing of commercially available ground monitors are discussed.

INTRODUCTION

Coal mine electrical power systems are often quite extensive, making a complete analysis untenable. Knowledge of the system characteristics is therefore spotty and must be continually revised as new properties and relationships are discovered.

CHARACTERISTICS OF THE MINE POWER SYSTEM

Conceptually, a mine power system is fairly simple, as shown in the block diagram in figure 1. The mine is usually fed by its own substation located on the surface. Voltage 38.5 kV or higher is transformed to the primary supply for the mine in the range from 13.2 to 4.2 kV. This high-voltage cable is usually fed down a steel cased borehole to a switch house or distribution box in the mine. There may be several of these boxes with branch circuits to feed power to all sections of the mine. Near the working face in each section is a power center, which transforms the voltage to 480 volts and distributes it to the various pieces of face equipment. The power center usually has a rectifier unit to supply dc for shuttle cars.

CHARACTERISTICS OF THE MINE GROUND SYSTEM

It has long been recognized that electrically powered machines pose a potential shock hazard, so that each piece of equipment is grounded through special conductors within its cable. The basic ground system is shown in figure 2.

Several features of the ground system deserve special attention. The ground system ideally is a tree structure; that is, it has several branches from each tie point, but has no loops. Theoretical analysis and practical experience tells us that a closed loop of wire is subject to large current flow induced by other currents in the vicinity since the power system itself acts like a large transformer.

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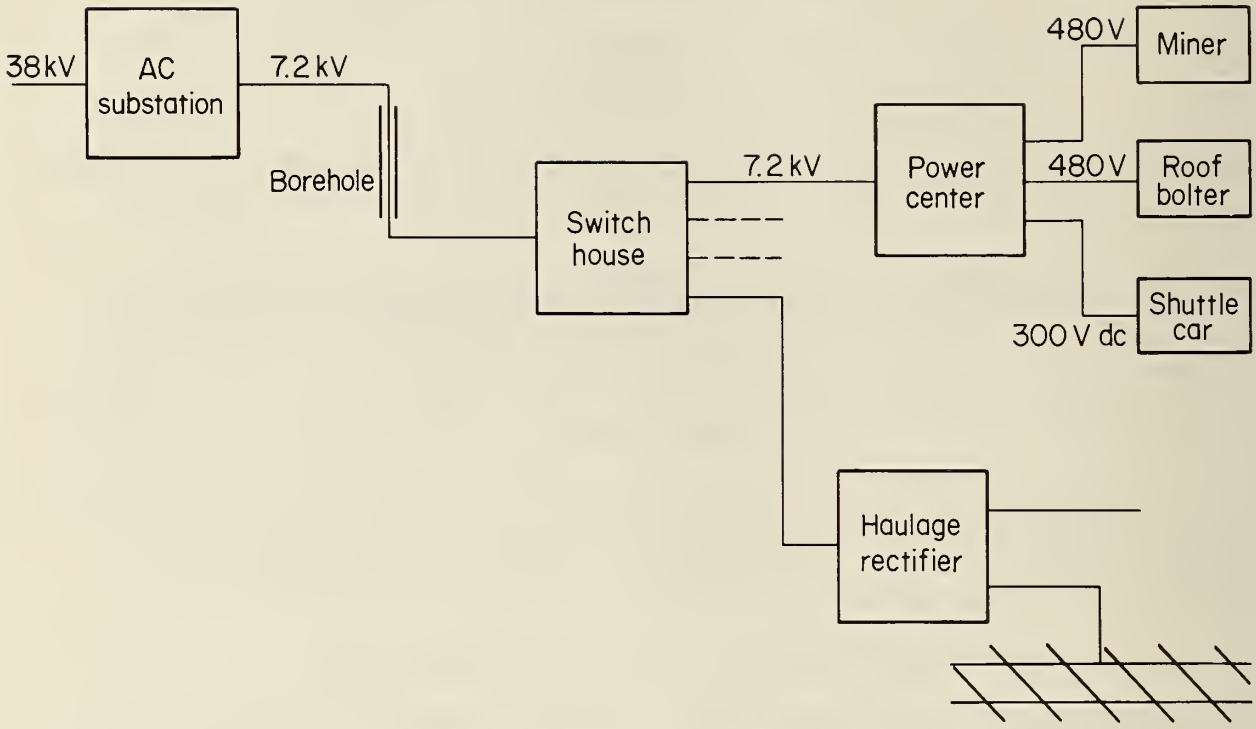

FIGURE 1. - Basic mine power system.

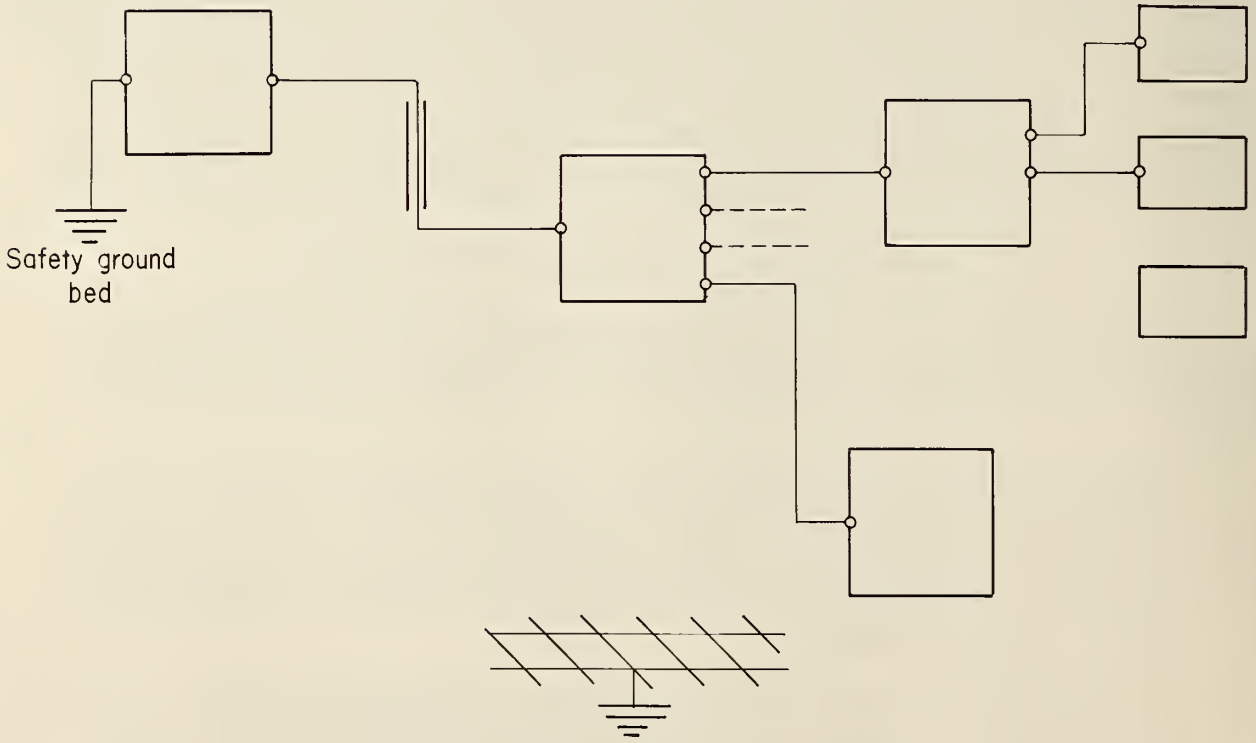

FIGURE 2. - Basic mine ground system.

The ground system is terminated at a ground bed located at the ac surface substation. The ground bed is simply an electrical connection to the earth to insure that the ground system is at earth potential.

Dc equipment is usually not connected directly to the safety ground system. It may be left entirely unconnected or grounded through diodes or other special grounding circuits. Therefore, no ground connection is shown for the shuttle car. The dc haulage system is also not connected to the safety ground. It is independently grounded, however, by its intimate contact with the floor of the mine. Nevertheless, significant differences in potential may exist between the track and the safety ground owing to the flow of haulage current within the track.

GROUND CHECK MONITORS

A ground check monitor is a device that is designed to detect the presence of an adequate electrical connection between certain parts of the mine safety ground system. If such a connection is not found, the monitor trips a breaker to remove power from the defective system. Since the ground conductor is not required for the operation of machinery, a failure of the ground connection may go undetected unless a ground check monitor is used.

In an ungrounded system, if a short develops between one of the phase conductors and the machine frame, then the entire machine becomes hot. This potential is harmless to the machine operator as long as he remains on his machines, much like a bird on a wire. If he simultaneously contacts his machine and earth, however, he provides a path for current flow that may kill him. A proper ground connector can prevent this by insuring that the machine frame is always near ground potential. The ground conductor offers protection in another way also. It provides a known return path in which current may be monitored for the purpose of interrupting power if a fault occurs.

REQUIREMENTS FOR LOW-VOLTAGE GROUND CHECK MONITORS

The Mining Enforcement and Safety Administration (MESA) requires that ground conductor monitors meet the following performance criteria:

1. If a ground check conductor is used, the ground check circuit will cause the circuit breaker to operate when the ground check conductor is broken.

2. The ground check circuit will cause the circuit breaker to operate if the ground wire is broken at any point in the grounding circuit. If low-resistance parallel paths for fault current and monitoring current are present, the ground check circuit will be acceptable if it is designed to open the circuit breaker when the impedance of the grounding circuit increases beyond the amount necessary to cause a 40-volt deop in the grounding circuit external to the grounding resistor under fault conditions.

3. Current flow in the ground check circuit will cause pickup of the ground check relay.

4. Ground check circuits, designed to provide undervoltage protection and installed to protect stationary equipment only, may utilize a small amount of time delay to prevent the ground check relay from causing nuisance tripping of the circuit breaker when harmless momentary drops in power occur and to prevent tripping of the circuit breaker of the ground check relay after an interruption of power when the circuit is reenergized. This time delay shall not exceed 15 cycles and shall not prevent the ground check circuit from immediately (without intentional delay) tripping the circuit breaker if the ground check or ground wire is broken.

The neutral point (or a transformer-derived neutral) of each power transformer is connected through a resistor to the ground system. This resistor is chosen to limit fault current to 15 amperes (usually) in the event of a phase-to-ground fault on the system. A ground fault detector relay is normally set to remove power from the system if the ground current exceeds 10 amperes. Federal regulations specify that the potential of a grounded machine frame must never exceed 40 volts (100 volts for a high-voltage system), even during fault conditions. Thus the ground circuit must be such that its impedance is below 4 ohms and preferably below 2.6 ohms (for low-voltage system). Although in most cases the ground system is either open or has very low impedance, under certain conditions a high impedance (4 ohms, for instance) can develop. A ground monitor must therefore be designed to trip at the proper impedance level rather than simply for an open circuit, especially if low-impedance parallel paths exist.

PROBLEMS ENCOUNTERED BY MONITORS

The very presence of the ground conductors in proximity to the phase conductors creates problems. The large currents in the phase conductors induce circulating currents in the ground conductors, which may cause an arc when two machines that have come into contact separate. Such arcs may contain enough energy to ignite an explosive mine atmosphere. Besides posing an explosion hazard, the circulating currents are often well in excess of that normally used for monitoring and can therefore render a monitor completely useless unless it has been properly designed.

If dc haulage equipment is operating in the vicinity of the ground conductors, stray dc currents may also be present in the ground system.

The starting of mine machinery creates additional problems of two types. First, the high currents required for starting may cause stray currents in the ground conductors that are 10 times more severe than the normal conditions just described. Second, the extra load on the power system may cause significant drops in the voltage (and hence power for the monitor) for a short time.

It is possible for a ground contact to be made with a machine other than the contact established through the safety ground system. Such a path may be through a metal waterline, another machine that comes into contact, or others. If the presence of an unsubstantial alternate or parallel path prevents the monitor from detecting a break in the primary ground conductors, then safety is not assured.

Safety considerations require that the ground check monitors be "fail-safe," meaning that any failure of the monitor itself will produce the same sort of alarm situation as a failure in the ground circuit.

Monitors are sometimes used to monitor the grounds of reel-type machines, the resistance of which fluctuates as the machine moves.

Under certain fault conditions, the monitor may be subjected to very large currents.

ADDITIONAL REQUIREMENTS FOR MONITORS

The previous discussion indicates that many situations can arise in the mine that would cause a failure in the monitor either through nuisance tripping or loss of ability to detect a faulty ground circuit. There follows a list of criteria that the ideal monitor should also satisfy in addition to those four criteria mentioned previously:

1. The ground wire monitor should function properly in the presence of stray ac and dc currents normally found on coal mine power system grounds. The occurence of very high stray currents should cause the monitor to indicate an unsafe condition.

2. Severe current and voltage transients are common on mine power systems. If the monitor derives its power from the mine power system, such transients should not damage the monitor or cause false indications of unacceptable ground circuits.

3. The ground wire monitor should be unaffected in its ability to monitor the ground circuit with variations of at least +20 pct to -30 pct of the nominal line voltage from which it draws its power.

4. The monitor should be designed as much as possible so that a failure of components within the monitor itself (including its power supply) will trip the circuit breaker.

5. The ground wire monitor should be capable of operating with the various sizes, types, and lengths of portable power cables normally found in the mine. No special training or extensive procedures should be required to calibrate the monitor when it is installed.

6. The ground wire monitor should not itself be capable of producing currents or voltages on the ground wire that are considered hazardous to mine personnel, either during normal operation or failure conditions.

7. The ground wire monitor should not affect the operation of other electrical components placed in the system, such as intermachine arc suppressors, ground fault locations, or other monitors in other branches of the system.

8. The ground wire monitor must continue to function properly in the presence of diode packs or other devices that have been inserted in the ground conductor provided these devices do not violate safety requirements.

9. The ground wire monitor should not be damaged by line-to-ground faults that are not cleared because of faulty trip units in circuit breakers.

10. If a ground check or pilot wire is used, the monitor should check the ground circuit all the way to and including the contact to the machine frame. It should signal an unacceptable condition if a pilot-to-ground fault develops within the system.

11. If the monitor is used on a reel-type machine, the ground wire is carried to the machine frame through a sliding contact (brush), During movement of the reel, the impedance of the contact can easily exceed 1.6 ohms for short periods (tenths of seconds). Such a situation should not cause nuisance tripping of the monitor.

12. Since the ground circuits are frequently bypassed by many unexpected ground paths, the monitor should operate properly in spite of these additional paths to ground.

13. Any device connected in series with the ground wire as part of the monitor must be capable of withstanding fault currents without burning open or increasing the impedance of the safety ground circuit. It should be capable of carrying as much current as the ground conductor itself.

The items listed are important to the effective operation of the ground check monitor. Some are not directly related to the safety of personnel but are concerned with the reliability of the device. Freedom from false tripping, for instance, is not a direct safety feature but is related to the acceptance of the device by the mine operators. As such, it should not be an official MESA testable safety criterion. This and other points that indirectly relate to safety are crucial to the development of highly workable systems and must be kept in mind.

MONITORING APPROACHES

A ground check monitor is simply a device to determine if the ground wire is continuous. There are several approaches to this problem that are outlined in figure 3.

All monitors require some flow of current in the ground wire in order to determine its resistance or continuity. This current may be classified as dc, ac, or audio. Dc monitors usually rectify the 480-volt, 3-phase power to provide current flow in the ground wire. AC monitors are defined as those which use a 60-Hz current derived from the phase conductors to assess ground wire continuity or impedance. Audio monitors are defined as those which generate their own test current with an oscillator. Monitors that use 2,500 Hz, 4,000 Hz, 900 Hz, 11 Hz, 8 Hz, and several different waveforms are all put into this category.

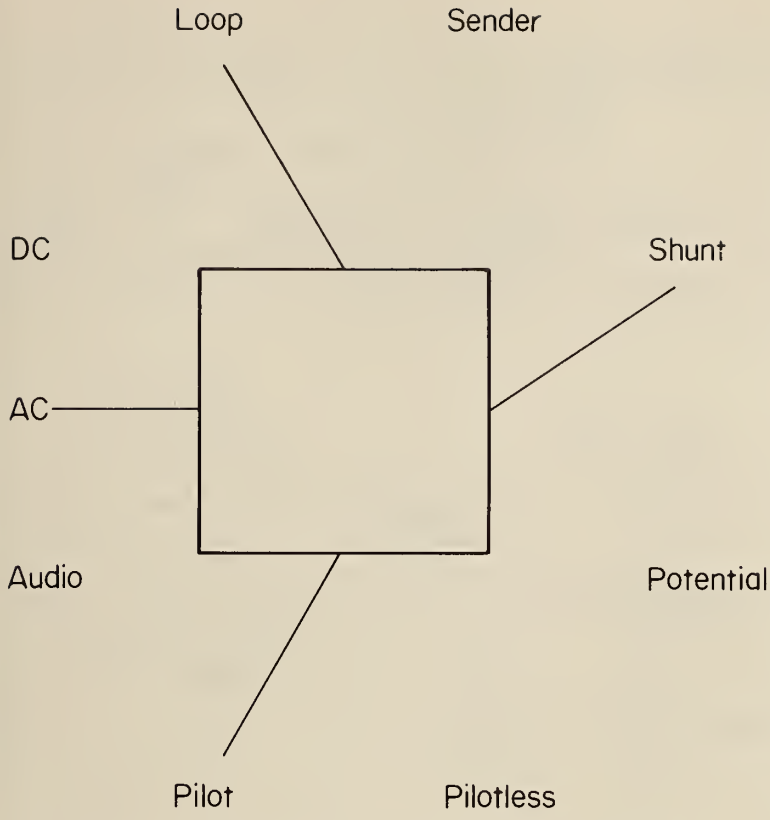

FIGURE 3. - Types of ground monitors. The lines are drawn to indicate one of the 24 possible combinations.

Monitors can be classified also according to their type of connection to the power system. Some monitors are connected in a loop configuration. The monitor applies a signal to the source (outby) end of a cable, either to the pilot wire or a phase conductor. The signal returns along the ground wire to the outby end of the cable, completing a loop by which the ground wire can be monitored (fig. 4).

Alternately, the monitor can consist of two separate units, a sender and a receiver. A sender located at the machine or load end of the cable sends a signal out on the ground conductor. This signal is picked up at the other end of the cable to determine continuity of the ground wire (fig. 5).

Monitors can be classified additionally as shunt detector or potential detector models. Shunt detector models actually sense current flow in the ground conductor. This can be accomplished with a current transformer or shunt or diode package in the ground wire (fig. 6).

Potential detectors measure the signal voltage that exists between the ground conductor and phase wire or pilot wire (fig. 7).

Finally, monitors may be classified as pilot or pilotless types, depending on whether they require a special wire in the cable that is neither a phase conductor nor ground wire.

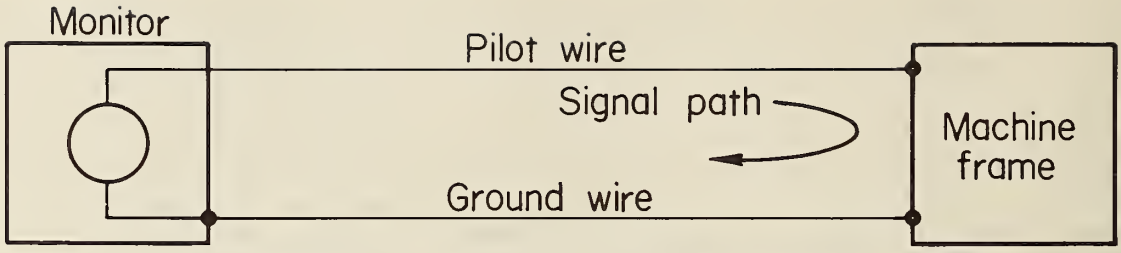

FIGURE 4. - Illustration of a loop-type monitor.

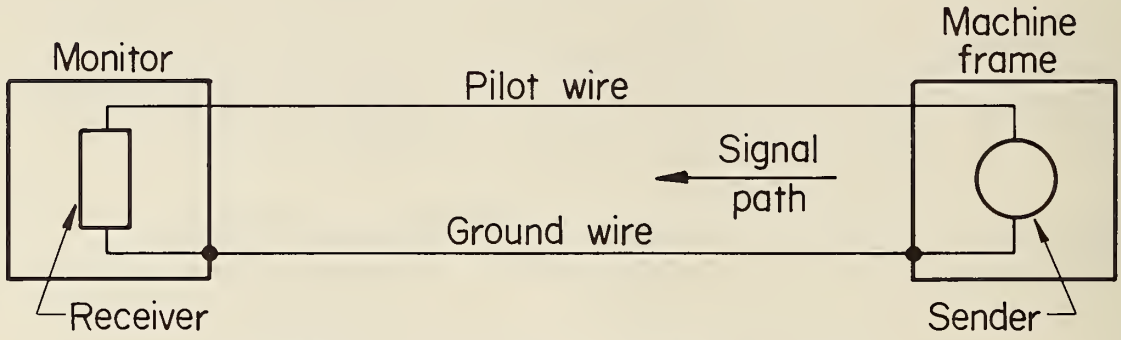

FIGURE 5. - Illustration of a sender-type monitor.

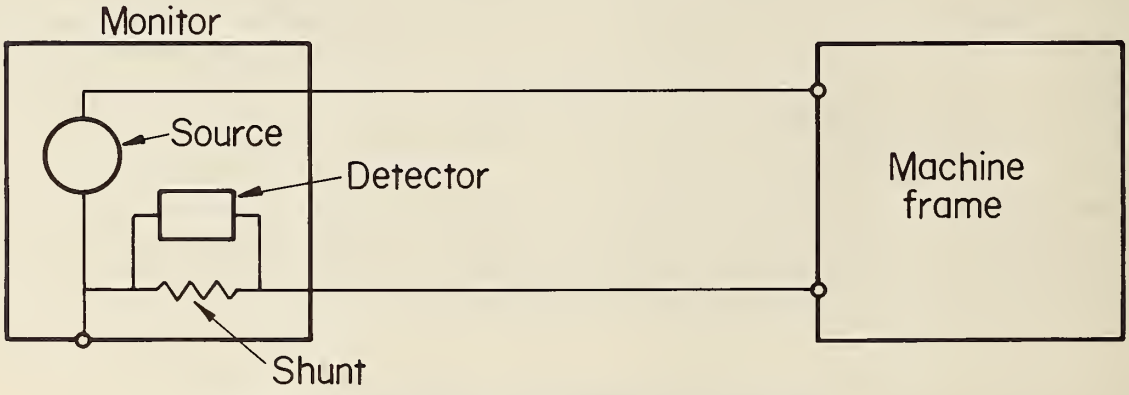

FIGURE 6. - Illustration of a shunt-type monitor.

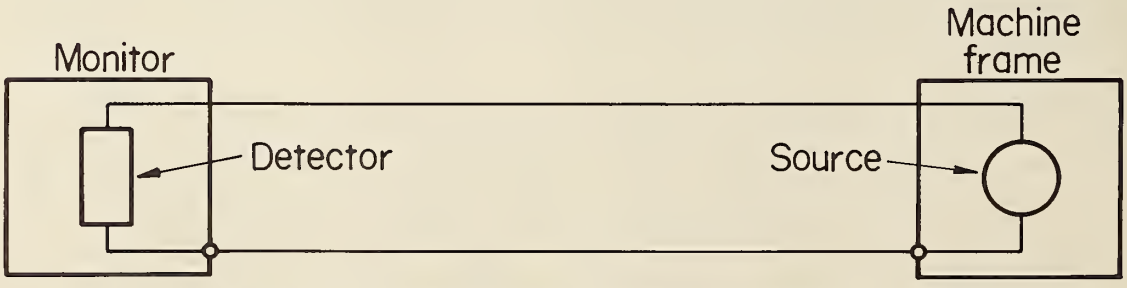

FIGURE 7. - Illustration of a potential-type monitor.

Monitors can be constructed using nearly any combination of the techniques listed (table 1). A few of the designs hold special interest, however, because of their ease of construction or high reliability.

TABLE 1. - Possible ground wire monitors

Flow of current	Type of connection to power system	Detector model	Pilot or pilotless type	Manufacturer
AC.....	Loop.....	Shunt....	Pilot.....	-
AC.....	.....do.....	...do....	Pilotless.....	West Virginia University.
AC.....	.....do.....	Potential	Pilot.....	Pemco. Ensign. Control products.
AC.....	.....do.....	...do....	Pilotless.....	-
AC.....	Sender.....	Shunt....	Pilot.....	-
AC.....	.....do.....	...do....	Pilotless.....	Ohio Brass Co.
AC.....	.....do.....	Potential	Pilot.....	-
AC.....	.....do.....	...do....	Pilotless.....	-
DC.....	Loop.....	Shunt....	Pilot.....	Westinghouse.
DC.....	.....do.....	...do....	Pilotless.....	-
DC.....	.....do.....	Potential	Pilot.....	FEMCO, Inc.
DC.....	.....do.....	...do....	Pilotless.....	-
DC.....	Sender.....	Shunt....	Pilot.....	-
DC.....	.....do.....	...do....	Pilotless.....	General Electric. Joy.
DC.....	.....do.....	Potential	Pilot.....	-
DC.....	.....do.....	...do....	Pilotless.....	-
Audio..	Loop.....	Shunt....	Pilot.....	-
Do...	.....do.....	...do....	Pilotless.....	-
Do...	.....do.....	Potential	Pilot.....	FEMCO, Inc.
Do...	.....do.....	...do....	Pilotless.....	Do.
Do...	Sender.....	Shunt....	Pilot.....	-
Do...	.....do.....	...do....	Pilotless.....	-
Do...	.....do.....	Potential	Pilot.....	Eltron.
Do...	.....do.....	...do....	Pilotless.....	Do.

TEST PROCEDURE

The basic characteristics of any monitor design can be determined by a review of its major design features. As indicated previously, various monitors have been designed to be insensitive to stray currents, parallel paths, etc. No circuit can be totally immune to these factors, however, and must be tested carefully to assess its actual performance.

The large variety of monitor schemes makes the design of a single generalized test procedure that would take in all possible situations for all the monitor systems very difficult. However, some simple measurements can give basic information that may be used to form a reasonably accurate picture of the monitor's probable performance.

The first thing measured is the impedance level at which the monitor operates. Around this basic point, measurements are made with various amounts of stray ac, stray dc, a simulated induced voltage, parallel paths, and supply voltage droop. The monitor's normal connections to the pilot and ground wires are instead connected to a test impedance. The test impedance contains both a variable resistor and an inductor to represent the self-inductance of the cable.

DC stray currents may be added to the test circuit by using a resistance and a voltage source to simulate a current source. The tests are conducted with various magnitudes and directions of current. The presence of stray ac currents may be simulated in a similar manner. If the source is eliminated, then the resistance can be used to test the effect of alternate parallel paths.

Transient testing has proven more difficult. Since heavy machinery is not available in the laboratory, it is necessary to simulate starting transients. Machine starting transients consist of large ac currents and dc current spikes, which require a complex circuit for proper simulation. This circuit has not yet been fully developed. However, an evaluation of the likely effects of starting transients was derived from a comparison of the effects of induced ac currents combined with tests on the effect of dc current spikes. Current spikes were delivered to the system with a simple capacitor discharge circuit. The capacitor was charged from a dc source and then discharged through a resistance onto the simulated ground conductor. The observed response of the monitors to the exponentially decaying current spike and to induced ac was used to estimate their response to the more complex current transients produced during machine starting.

FIELD TESTS

Twenty-four monitors supplied by four different manufacturers have been field tested in several area mines. These units and others were also extensively tested in the laboratory. These monitors were all of the more sophisticated shunt-sender or audio types. They were installed according to manufacturers instructions except that the trip signal was fed to an event counter rather than the breaker release. Units were placed on miners, roof bolters, shuttle cars, and other pieces of face equipment.

Numerous problems were encountered with installation and operation of the monitors, and a few situations arose in which it was impossible to physically install the monitors in the available space. Others required much rerouting of wires, adjustments within the power center while it was on, and makeshift mounting. All the monitors are poorly packaged with apparently little thought given to the mechanics of installation.

Some of the units have been in place for several months, and as yet none has functioned satisfactorily. All monitors have experienced excessive false tripping, sometimes hundreds of trips per shift. Table 2 indicates the results of evaluations to date.

TABLE 2. - Relative performance of several monitor designs

		M1	M2	M3	M4	M5	M6	M7	M8
1.	Trips at 1.6 ohms.....	E	F	P	P	P	P	G	F
2.	Immune to ac.....	E	P	F[1]	E	E	E	E	E
3.	Immune to dc.....	E	E	F[1]	P	G	G	E	E
4.	Immune to transients.....	P	F	U	G	U	G	E	G[1]
5.	Immune to voltage droop.....	E	P	U	G	U	E	F	E
6.	Failsafe.....	G	E	E	E	E	E	F	E[1]
7.	Minimal adjustment.....	G	E	E	E	E	NAp	P	G[1]
8.	No hazardous voltages.....	E	E	E	E	E	E	F	E
9.	Compatible with other devices....	E	E	E	E	E	E	E	E
10.	Undamaged by faults.....	E	E	E	E	E	E	E	G[1]
11.	Work with pilotless cables.....	E	P	E	P	E	E	E	E
12.	Detects pilot-ground fault.....	NAp	P	NAp	E	NAp	NAp	P, NAp	E
13.	Works through reel contact.....	P	P	U	G	U	G	F	G[1]
14.	Immune to parallel paths.....	E	U	G	E	G	E	G	P
15.	Preserves ground wire integrity..	E	E	G	G	G	G	F	E
16.	Easy to reinitialize.....	E	E	F	E	E	F	E	E
17.	Unaffected by reclosing breakers.	P	F	U	F	U	P	F	G[1]

[1]Estimated only--subject to change.
M1--Negative sequence filter--West Virginia University.
M2--AC series relay--Ensign.
M3--AC sender, pilotless--Ohio Brass Co.
M4--DC loop, shunt detection, machine mounted resistor--Westinghouse.
M5--DC sender, shunt detector, pilotless--Joy.
M6--DC sender, shunt detector, pilotless--General Electric.
M7--Audio frequency, pilot or pilotless, tuned filter--FEMCO.
M8--Audio frequency with sender unit, pilot or pilotless--Eltron.
E--Excellent.
G--Good.
F--Fair.
P--Poor.
NAp--Not applicable.
U--Unknown.

MONITOR APPROACHES TESTED

The most basic and most common type of monitor is the simple series relay. This is a loop-potential-pilot type monitor and is constructed in both ac and dc versions (fig. 8). Several manufacturers incorporate this type monitor into their switch houses and power centers, so that about 90 pct of the monitors in the field are of this type. Control Products, Ensign Electric, Pemco,[3] and possibly some other companies manufacture monitors of this type. These monitors are inexpensive and easy to use, are highly reliable in terms of component failure, and are safe and compatible with the rest of the system. They have several disadvantages, however. They are sensitive to stray currents on the ground system, which usually results in a great many nuisance

[3]Reference to specific manufacturers does not imply endorsement by the Bureau of Mines.

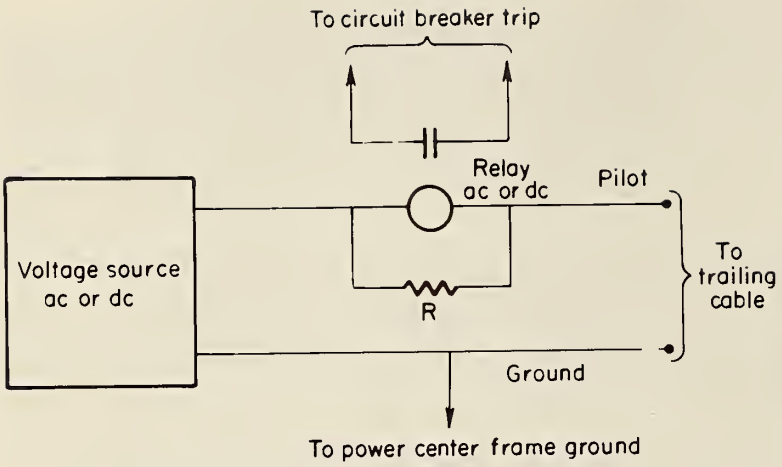

FIGURE 8. - Series relay monitor.

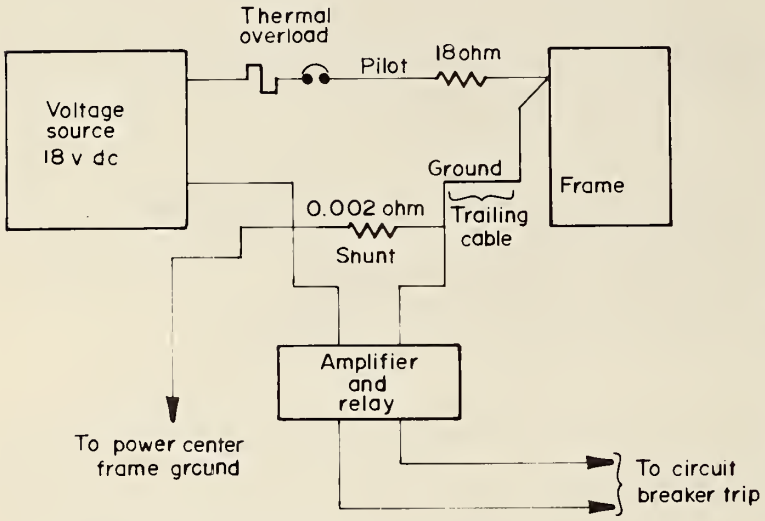

FIGURE 9. - DC monitor with shunt detection.

trips if substantial stray currents are present. They fail to monitor the ground if parallel paths or pilot-to-ground faults exist. In addition, they are sensitive to powerline voltage fluctuations, which greatly influence the ground wire resistance levels that are considered acceptable to prevent excessive voltage rise on machine frames. The authors have tested only one of this type, built by Ensign Electric. The results are shown in table 2.

The next type of commercially available design that was tested is a dc-loop-shunt-pilot-type monitor available from Westinghouse. Figure 9 shows a block diagram of this monitor. This monitor is designed to have several advantages over the previous types. The 18-ohm machine resistor and thermal overload breaker are used to detect a pilot-to-ground fault on the cable, avoiding this serious shortcoming of many monitors. Its design makes it immune to stray ac current on the ground system, and the shunt detection scheme makes it immune to parallel paths to ground. It remains sensitive to stray dc current, however, and is quite expensive. Table 2 shows its relative strengths and weaknesses.

A third commercially available design is an audio-loop-potential type monitor manufactured by Femco, Inc., a division of National Mine Service. It is available in both a pilotless version and a pilot version, shown in figure 10. The transformer matches the impedance of the voltage source to the cable for increased sensitivity. Although the circuit shows a shunt, this device does not actually measure current flow in the ground conductor and is, therefore, not a true shunt detector. The saturable reactor is an arc suppression device, which does double duty by helping to make the monitor insensitive to parallel ground paths. This monitoring approach is well conceived and has several advantages. The design is totally immune to both stray

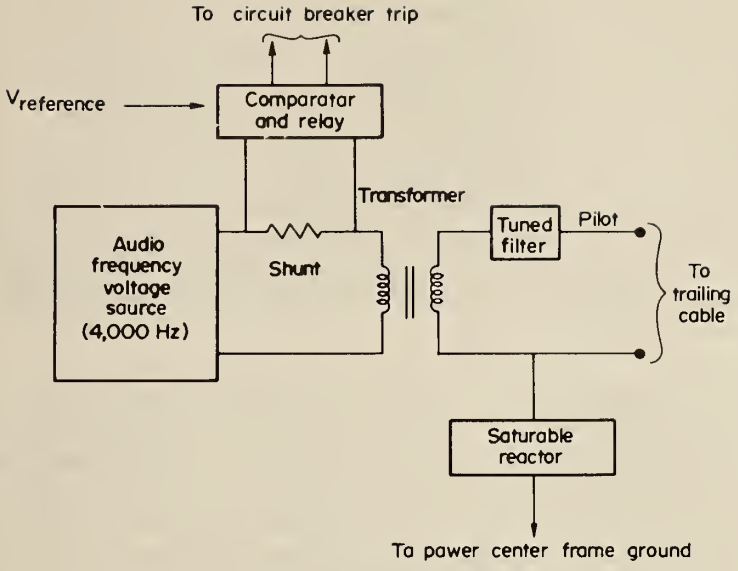

FIGURE 10. - Audio frequency with impedance transformer.

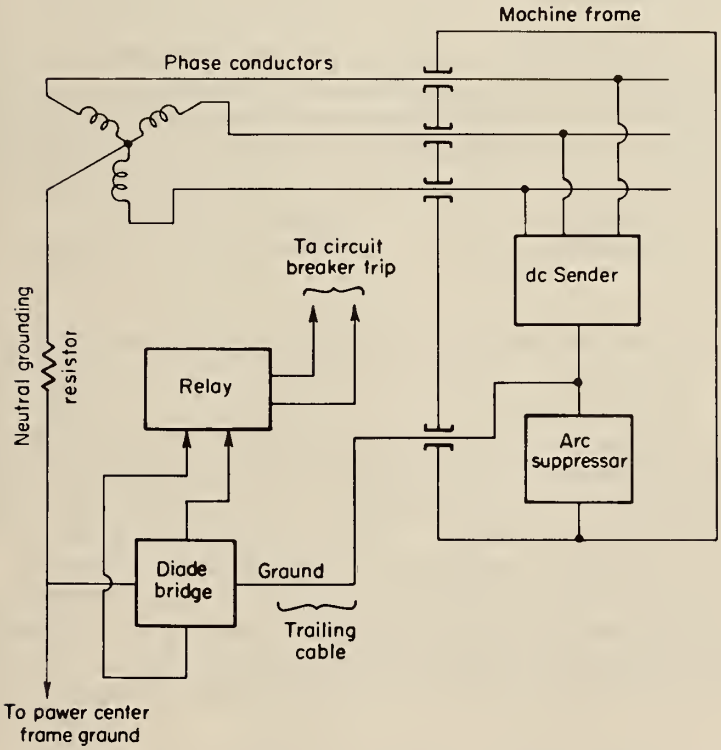

FIGURE 11. - Pilotless dc with diode sender and diode bridge detection.

ac and stray dc. It has its own regulated power supply and is hence unaffected by voltage droop. It is compatible with other system components and can be adjusted to accurately differentiate between proper ground connections and high-resistance ground paths. The monitor does have several disadvantages, however. Probably the most significant is the necessity to make one or more operating adjustments in the field after installation of the monitor. On at least two occasions, personnel were observed to have carried out the adjustments incorrectly, causing the monitor to completely lose its ability to detect an open ground, thereby rendering it totally useless. Even when done correctly, the need to make adjustments within the power center enclosure while the power was on endangered the personal safety of the installer.

Pilot version of the FEMCO monitor does not detect pilot-to-ground faults unless some rather fine adjustments are made to the monitor. There is some concern that the pilotless version could apply hazardous potentials to the machine frame if the ground should be broken or if the filter should fail. A circuit redesign to correct this problem has proven successful.

A fourth type of monitor is available in very similar designs from two manufacturers. This is a dc-sender-shunt-pilotless type, marketed by General Electric and Joy Manufacturing. Figure 11 shows a block diagram of this design. Current flow in the ground conductor is detected as the potential across a diode bridge. A zigzag transformer and diodes placed in a sender unit to be mounted on the machine provide a small dc current flow in the ground circuit. These two monitors have similar characteristics. They are moderately immune to stray currents, in that the diode bridge shunt rectifies all stray ground current, preventing nuisance trips. The devices are safe and compatible, and their shunt detection feature makes them immune to parallel paths. Both monitors also have the ability to detect a pilot-to-ground fault and hence monitor the entire ground wire.

These monitors have several disadvantages. Both are rather complex and expensive. They have proven very difficult to install because of the need to place the sender unit within the explosion-proof enclosure of the face machine. Bulky, poorly packaged units were easily damaged during installation or would not fit at all. Neither monitor is properly sensitive to the resistance of the ground conductor. The General Electric monitor rated as acceptable ground impedances in excess of 1,000 ohms; the Joy monitor continued to hold in even when the ground conductor was completely severed and the two bare ends held by one of the test personnel. This insensitivity is intolerable. The General Electric monitors have been plagued by excessive false trips and have never operated successfully in our field tests.

The Ohio Brass Co. markets a similar device that uses an unbalanced capacitive load to produce an ac voltage on the ground wire instead of dc. It is essentially the same as figure 11 in all other respects. This monitor failed to operate in several instances, seemingly because the design is overly sensitive to small changes in the characteristics of the pickup relay. The sender unit is very bulky and hard to install, and its design may cause hazardous voltages to appear on the machine frame if the ground wire becomes disconnected.

The relative performance of all three of these monitors are shown in table 2.

A monitor designed by Eltron, Corp. is nearly ready for production. It is an audio-sender-potential device that can be used either in the pilot configuration or pilotless configuration. It is designed to be immune to stray ac and dc currents and parallel ground paths. It is supposed to be safe and compatible, and sensitive to ground conductor resistance. Although a monitor has not been received for testing, the authors believe it will have several disadvantages. It is complex and probably expensive and requires an operating adjustment. There will probably be problems with installation, and there may be problems similar to those encountered with the FEMCO device.

West Virginia University is developing two ground monitors. The first is an ac-loop-shunt-pilotless monitor. This device monitors the ground conductors by sensing the normal induced currents in an intact cable. It is extremely sensitive and will even drop out if only one of the three ground wires

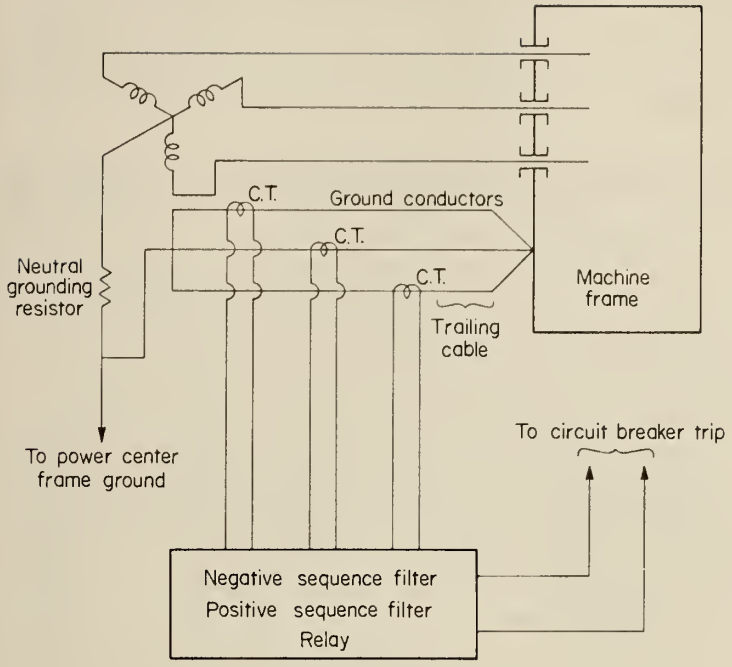

FIGURE 12. - Negative sequence filter monitor.

of a type G cable is broken. It is immune to stray currents and parallel paths. Its disadvantages are that it is complex and may require adjustment. Its ability to monitor depends on keeping the ground conductors separate throughout the entire circuit, which requires changing cable couplers and connectors. Testing of this monitor is in its first stages. The block diagram of this device is shown in figure 12.

West Virginia University is also developing a modular ground wire monitoring system. This approach recognizes that no single monitoring technique is maximally cost-effective in all situations. This monitor system consists of a main frame unit with several plug-in modules that can be used singly or in combination to provide the proper amount of sophistication required for each mine. The goal of this system is to reduce the cost of effective monitoring by increasing flexibility. Several modules have been constructed and are being tested.

SUMMARY

The results of laboratory and field testing indicate that ground check monitoring has progressed but there is still room for much improvement. There is still no monitor that is totally effective. The basic ac and dc loop-potential-pilot monitors are quite effective under ideal conditions. Several of the modern designs discussed offer substantial improvements in quality of monitoring but suffer from other problems. There are flaws in some designs, poor quality construction, and problems with installation and operation.

The choice of monitor system should be dependent on the environmental conditions in the mine and the priorities of management. As one can see from the test data, the new designs have very different characteristics from one manufacturer to the other. Greatly improved monitors do exist, but they must be chosen carefully and installed correctly before reliable service is possible.

TRAILING CABLE SPLICING--ACCEPTANCE TESTING AND TRAINING

by

Robert King[1]

ABSTRACT

Splicing portable trailing cables used in underground coal mines is usually less expensive in terms of capital outlay and production time lost than replacing them. However, handling trailing cables may result in electrical arcs, shocks, and burns. Also, destructive forces encountered during a mining operation may shorten the effective life of a cable splice. This report gives the results of an analysis of cable splice defects in an effort to establish cable splice performance criteria, determine testing standards for cable splices, establish guidelines for training programs in cable splicing, and indicate areas for improvement.

INTRODUCTION

Portable trailing cables used in underground coal mines are frequently damaged by mobile equipment and fallen rock or coal. To prevent fires or methane ignitions resulting from electrical arcing and to restore power to production machinery, the cables must be repaired or replaced. Repairing, which is accomplished by splicing (the mechanical joining of one or more severed conductors), is usually less expensive in terms of capital outlay and production time lost than replacement. However, splicing is not a simple operation, and incorrectly applied splices frequently break down, resulting in high costs from production delays. Frequent repairs increase splicing tools, materials, and labor expenditures.

Safety is also decreased by trailing cable splicing. A Mining Enforcement and Safety Administration (MESA) study covering the year 1973 indicates three fatalities from electrocution of victims working with trailing cables. In addition, electrical arcs, shocks, and burns from handling trailing cables were shown in the report to have caused 129 injuries. Also, 38 injuries occurring during the process of making splices are documented; therefore, a definite safety hazard exists.

These economic and safety problems are present even after the Coal Mine Health and Safety Act of 1969 restricted the number of temporary splices in a trailing cable to one for a 24-hour period. However, there is no restriction on the number of permanent splices. As a result, several splice kits are being marketed with flame-resistant jackets (qualifying them as permanent repairs). Such kits allow quick repairs to be made underground.

[1]Assistant professor, Pennsylvania State University, University Park, Pa.

Concern over the safety and production delay aspects of these so-called permanent splices resulted in the Federal Bureau of Mines funding a cable splice evaluation research project under grants G0101729 and G0133077. R. Stefanko and L. A. Morley directed the projects, which were monitored by George Conroy, the Bureau of Mines technical project officer.

The report that follows briefly outlines the research completed and gives the more interesting results. A complete literature search is included in the final report of the grants previously mentioned. Also, detailed test procedures, sample descriptions, test data, and detailed discussion of results are contained in the final report.

ANALYSIS OF CABLE SPLICE DEFECTS

Currently the MESA Div. of Approval and Testing approves splices on the basis of a flame-resistant outer jacket. But underground coal mine conditions cause many other destructive forces; consequently, additional tests should be performed to insure that a properly constructed splice will withstand destructive forces encountered during a mining operation. Analyzing the forces imposed on a mining trailing cable during normal operation resulted in a series of tests that were performed at Penn State on 184 splices. In addition to providing basic engineering information for improving splicing product design and splicing techniques, the tests were recommended to MESA for the approval process. Another consequence is comparison data for performance criteria for splice kit choice, since the simple test apparatus can be purchased by mining companies.

Normal underground cable environment dictates checking conductivity, moisture penetration, flexibility, tensile strength, dielectric breakdown voltage, and abrasion properties. Since shuttle car operation proves to be the most deleterious to splices, the common flat "buggy" cable number two and four AWG, types W and G, comprise the test group. Manufacturer-provided splices (centered in 6- to 8-foot cable lengths) are common specimens. The tests will be briefly explained in the following paragraphs. Results, recommended specifications, and conclusions will complete the report.

The conductivity test apparatus is a Leeds and Northrup 4288-2 Kelvin Bridge[2] (fig. 1) for determining joint resistance. Measurements indicated all connection types were able to obtain near zero resistance. Maximum values obtained were 0.4 mΩ on a number two AWG conductor, 0.5 mΩ on a number four AWG conductor, 1.3 mΩ on a number six AWG ground wire, and 0.9 mΩ on a number eight AWG ground wire. (The number six AWG connection was improperly constructed.) These maximum resistances are not high enough to cause significant splice heating. Therefore, splice joint heating results from improperly made or partially broken connections. Additionally, high crimping forces are not necessary to produce adequate conductivity. Nevertheless, tensile pullout can result from undercrimped connections.

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[2]Reference to specific products does not imply endorsement by the Bureau of Mines.

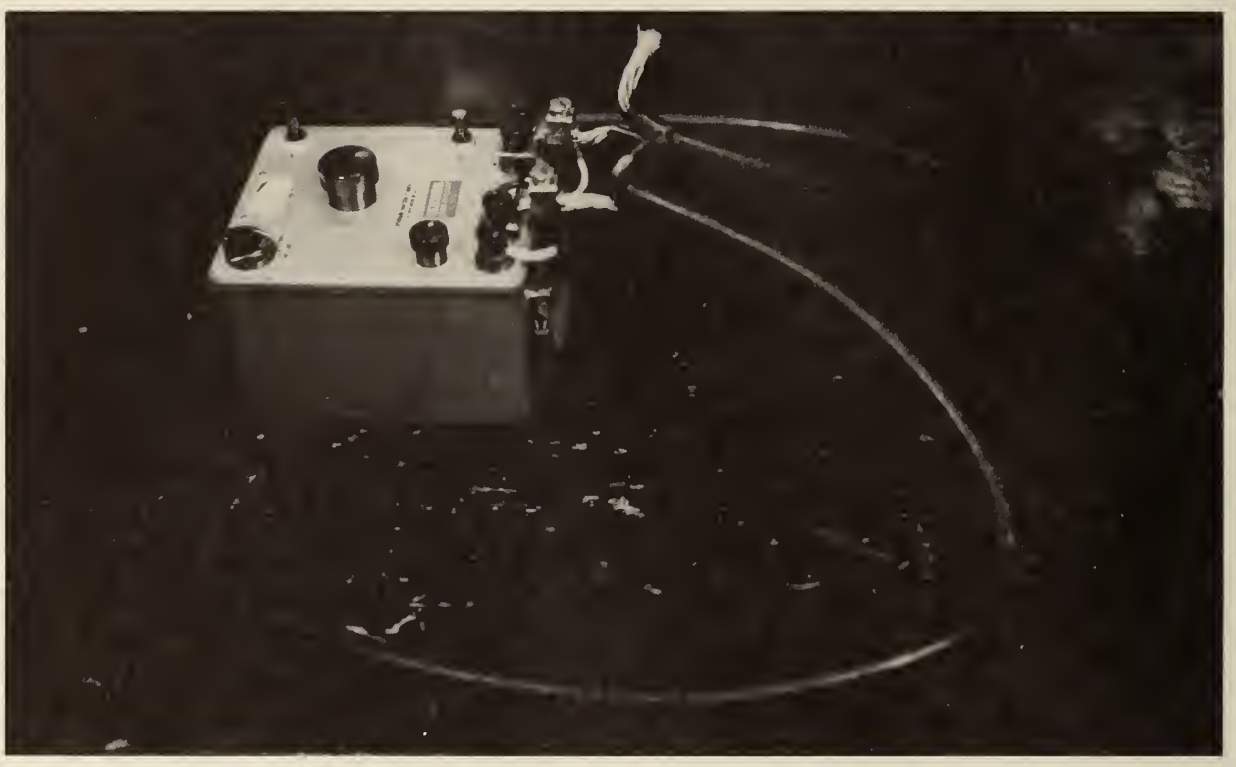

FIGURE 1. - Conductivity test apparatus (number four AWG type W cable).

FIGURE 2. - Insulation and moisture resistance test apparatus (number two AWG type W cable).

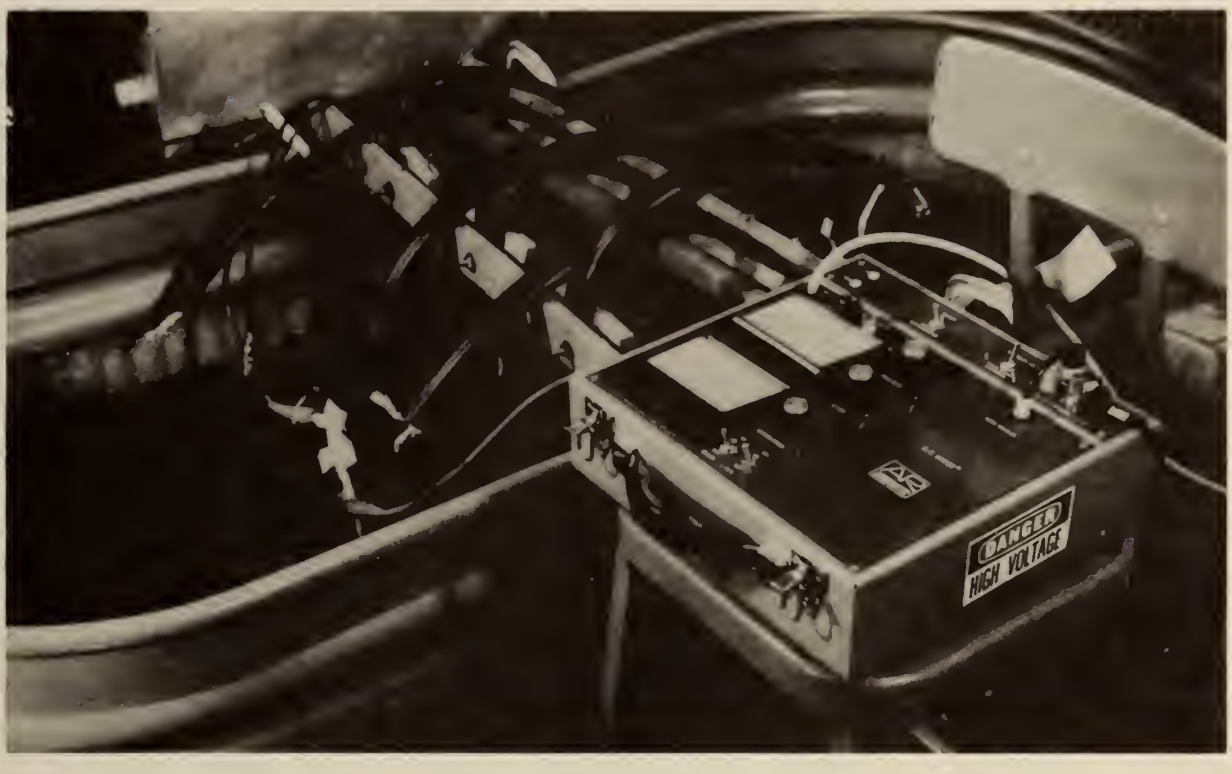

FIGURE 3. - Dielectric breakdown voltage test apparatus (number two AWG type G cable).

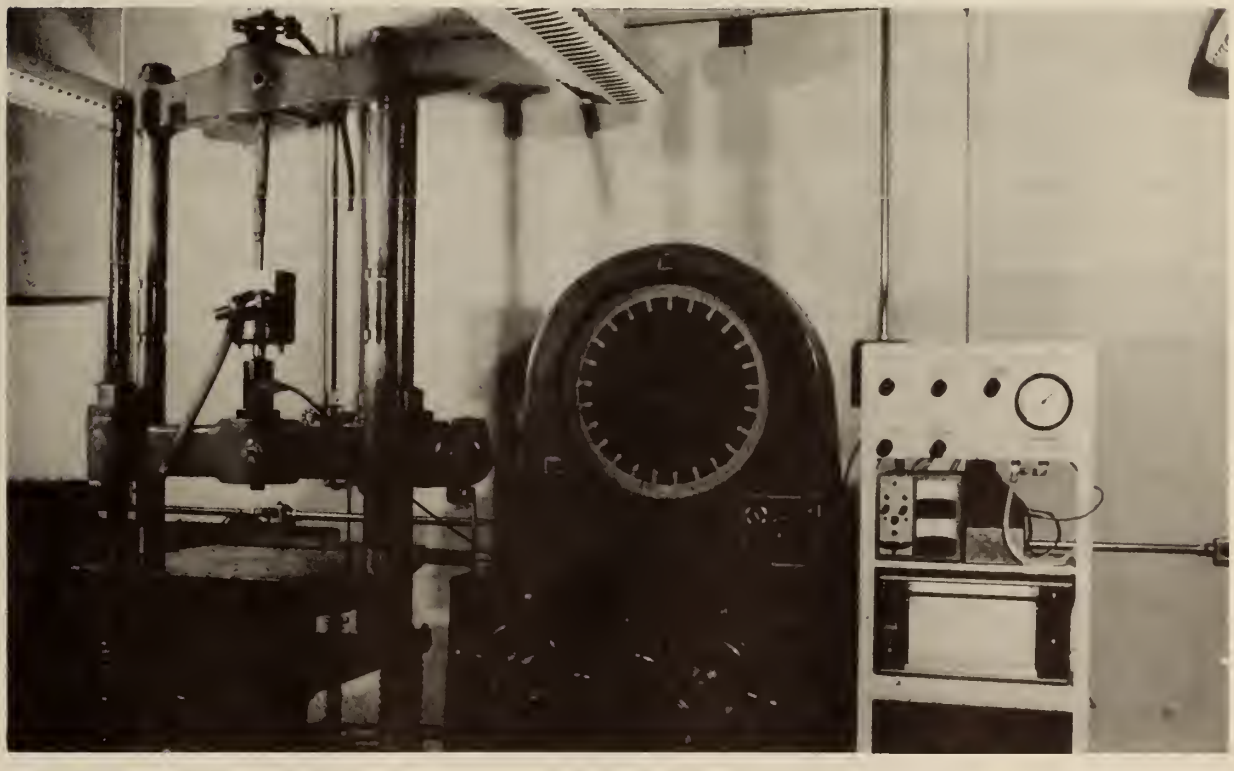

FIGURE 4. - Tension apparatus (number two AWG type G cable).

Moisture resistance is measured, as indicated in figure 2, with a 500 V J.G. Biddle Meggar after the splice is immersed in a water bath. Generally, all splice jackets exhibit poor moisture resistance when improperly applied. However, a properly cleaned cable surface and correct application of adhesives result in adequate moisture resistances for all jacket types. Nevertheless, flexing deleteriously affects all bonds except vulcanized bonds since bending the splice to cable jacket contact tends to put the adhesive under a tension that separates the contact. When adhesive was applied throughout the splice length, moisture is excluded from contacting the phase or ground wires even though flexing causes the ends to open.

A dielectric voltage withstand test is conducted with the Associated Research Hypot shown in figure 3. The voltage is incremented in 500-V dc steps until the instrument range (15,000 volts) is reached. Results indicate all insulations have sufficient strength to withstand the electrical forces imposed on trailing cables before flexing. However, after flexing, withstand voltages dropped to unacceptable levels in some splices, and tape insulations were particularly damaged by flexing. Dielectric breakdowns were not a result of the insulation electrical quality but of the resistance to puncture from wires and connector edges or of the existence of voids. Therefore, most failures resulted from workmanship defects such as

1. Leaving wire strands unconfined to puncture insulation.

2. Cutting insulation with a knife during cable preparation and neglecting to reinsulate the damaged area.

3. Sharp-edged connectors and crimp deformations.

To determine tensile strength, splices are mounted in a Baldwin Universal Testing Machine (fig. 4) and the total multiconductor splice is tensioned to failure. Results indicate that welded splices have consistently higher tensile strength than mechanical crimps (83.9 pct compared with 53.4 pct). See table 1. Also, tensioning multiconductor splices reveals the importance of even length conductors; slight length difference causes one conductor to carry most of the load. The following errors caused inadequate pullout strength:

1. Not crimping on the connector center.

2. Applying the wrong size connector.

3. Not using recommended crimping force.

4. Not inserting all of the strands into the connector.

5. Not pushing the strands completely into the connector.

6. Not using the proper crimping tool.

TABLE 1. - Tension summary

Group	Cable	Connector	Jacket and insulation	Tensile strength, lb	Original cable, pct
U	2,W	Staggered weld..	Vulcanized.....	3,800	100
V	2,G	Butt weld.....	.....do.....	4,670	100
JJ	4,G	Crows foot.....	Heat shrink.....	2,813	94
JJ	4,G	.....do.....	.....do.....	2,627	88
II	2,G	Butt weld.....	.....do.....	4,093	86
S	4,W	.....do.....	Uninsulated.....	2,000	83
FF	2,G	.....do.....	Vulcanized and heat shrink.	3,865	81
P	4,G	Butt.....	Cold splice.....	2,265	76
HH	2,G	Butt weld.....	Vulcanized.....	3,616	76
H	2,G	Crows foot.....	Heat-shrink.....	3,430	72
Y	2,G	Lap.....	.....do.....	3,340	70
JJ	2,G	Crows foot.....	.....do.....	3,287	69
L	4,G	Butt.....	Cold splice.....	1,900	63
M	4,W	.....do.....	.....do.....	1,480	62
Q	2,G	.....do.....	.....do.....	2,915	61
S	2,G	Butt weld.....	Uninsulated.....	2,900	61
G	4,W	Lap.....	Tape.....	1,370	57
BB	4,W	Butt.....	Heat-shrink.....	1,347	56
I	2,G	Crow foot.....	.....do.....	2,620	55
K	2,W	Butt.....	Cold splice.....	2,060	54
O	4,G	.....do.....	.....do.....	1,630	54
GG	2,G	Lap.....	Tape.....	2,480	52
AA	4,G	Butt.....	Heat-shrink.....	1,533	51
A	2,G	.....do.....	Cold splice.....	2,390	50
B	2,G	.....do.....	.....do.....	2,390	50
R	2,W	.....do.....	.....do.....	1,840	48
C	4,G	.....do.....	.....do.....	1,420	47
D	4,G	.....do.....	.....do.....	1,420	47
J	2,G	.....do.....	.....do.....	2,250	47
X	4,W	Lap.....	Heat-shrink.....	1,120	47
W	4,G	Lap.....	.....do.....	1,327	44
F	2,W	Lap.....	.....do.....	1,610	42
Z	2,W	Lap.....	.....do.....	1,520	40
N	2,G	Butt.....	Cold splice.....	1,640	34
E	2,G	Lap.....	Tape.....	1,580	33
CC	2,G	Butt.....	Heat-shrink.....	1,560	33
DD	2,W	.....do.....	.....do.....	1,187	31
EE	4,W	Lap.....	.....do.....	660	28

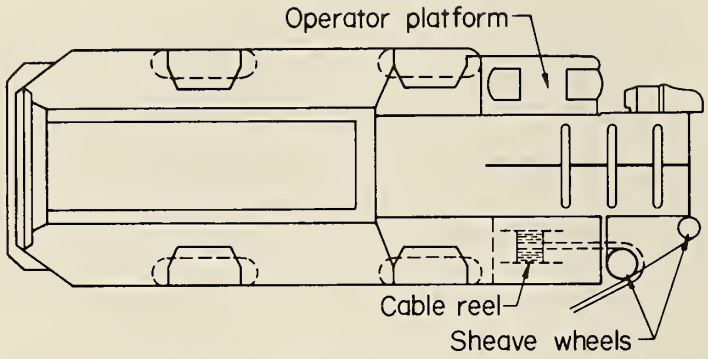

FIGURE 5. - Shuttle car—plan view.

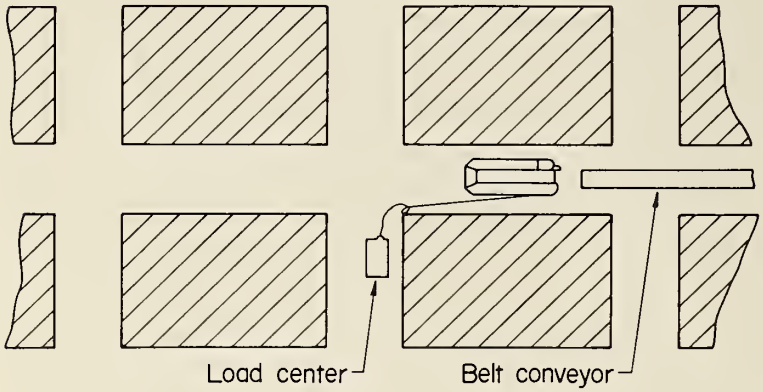

FIGURE 6. - Shuttle car back spooling at dumping point.

The test for flexibility is based on the shuttle car action of reeling in and paying out cable as shown in figures 5-6. The apparatus depicted in figure 7 simulates shuttle car cable bending around the sheave wheels. The worst case, 180° bending under a constant 175-pound tension, is assumed; as a result, 1 month underground operation may represent from 100 to 500 flexing machine cycles depending on severity of mine conditions. The longest flex life recorded in table 2 is 11,737 cycles, which does not compare favorably with an unspliced cable that flexes 40,000 cycles without completely failing. As a result of data collected, the following design rules will improve flexing performance:

1. Reduce straight rigid section length.

2. Taper the crimp toward the connector edge to diminish point stress concentration.

3. Round connector edges.

4. Provide a conductor support sleeve at the connector or crimp edge.

Observation of failed samples reveals that many mine workers mistake flex breakage for tensile pullout. Consequently, bending failures along with moisture penetration are the most common types of splice failure.

TABLE 2. - Flexibility summary

Group	Cable	Connector[1]	Insulation	Initial failure, cycles	Complete failure, cycles
GG	2,G	Lap.....	Tape.....	23	11,737
G[2]	4,W	Lap.....	.....do.....	2,426	9,331
EE	4,W	Lap.....	Heat-shrink.....	360	5,910
X	4,W	Lap.....	.....do.....	50	4,824
Z	2,W	Lap.....	.....do.....	75	4,048
W	4,G	Lap.....	.....do.....	35	3,273
U	2,G	Staggered weld.....	Vulcanized.....	41	2,490
HH[2]	2,G	Butt weld.....	.....do.....	83	2,433
W	2,G	Butt.....	Cold splice.....	276	2,321
JJ	2,G	Crows foot.....	Heat-shrink.....	36	2,070
Y	2,G	Lap.....	.....do.....	70	1,763
DD	2,W	Butt.....	.....do.....	595	1,734
BB	4,W	.....do.....	.....do.....	20	1,705
S	4,W	Butt weld.....	Vulcanized.....	28	1,633
I	2,G	Crows foot.....	Heat-shrink.....	175	1,592
V	2,G	Butt weld.....	Vulcanized.....	62	1,345
F[2]	2,W	Lap.....	Heat-shrink.....	73	1,333
AA	4,G	Butt.....	.....do.....	38	1,206
FF	2,G	Butt weld.....	Vulcanized.....	85	930
FF	2,G	.....do.....	Heat-shrink.....	51	[3]550
R	2,W	Butt.....	Cold splice.....	138	471
CC	2,G	.....do.....	Heat-shrink.....	101	450
M	4,W	.....do.....	Cold splice.....	159	440
J	2,G	.....do.....	.....do.....	46	400
O	4,G	.....do.....	.....do.....	30	380
Q	2,G	.....do.....	.....do.....	14	[3]325
L	4,G	.....do.....	.....do.....	45	301
K	2,W	.....do.....	.....do.....	81	289
H	2,G	Crows foot.....	Heat-shrink.....	27	[3]232
JJ	4,G	.....do.....	.....do.....	19	[3]220
P	4,G	Butt.....	Cold splice.....	6	[3]215
JJ[2]	4,G	Crows foot.....	Heat-shrink.....	43	[3]129
FF	2,G	Butt weld.....	.....do.....	23	[3]125
II[2]	2,G	.....do.....	.....do.....	5	[3]63
JJ	4,G	Crows foot.....	.....do.....	1	[3]19

[1]Mechanical crimp unless otherwise specified.
[2]Made at underground mines.
[3]Ground wire failure.

An abrasion test is conducted using the flexing machine apparatus modified with two abrasive cylinders and a constant force roller as shown (fig. 8). Performance indicates tape splices have least abrasion resistance (150 to 386 cycles); cold splices are next (532 to 10,000 cycles). Vulcanized and heat shrink splices have the greatest abrasion resistance (greater than 10,000 cycles). Workmanship defects also affected abrasion since loose strands protrude through the insulation and jacket.

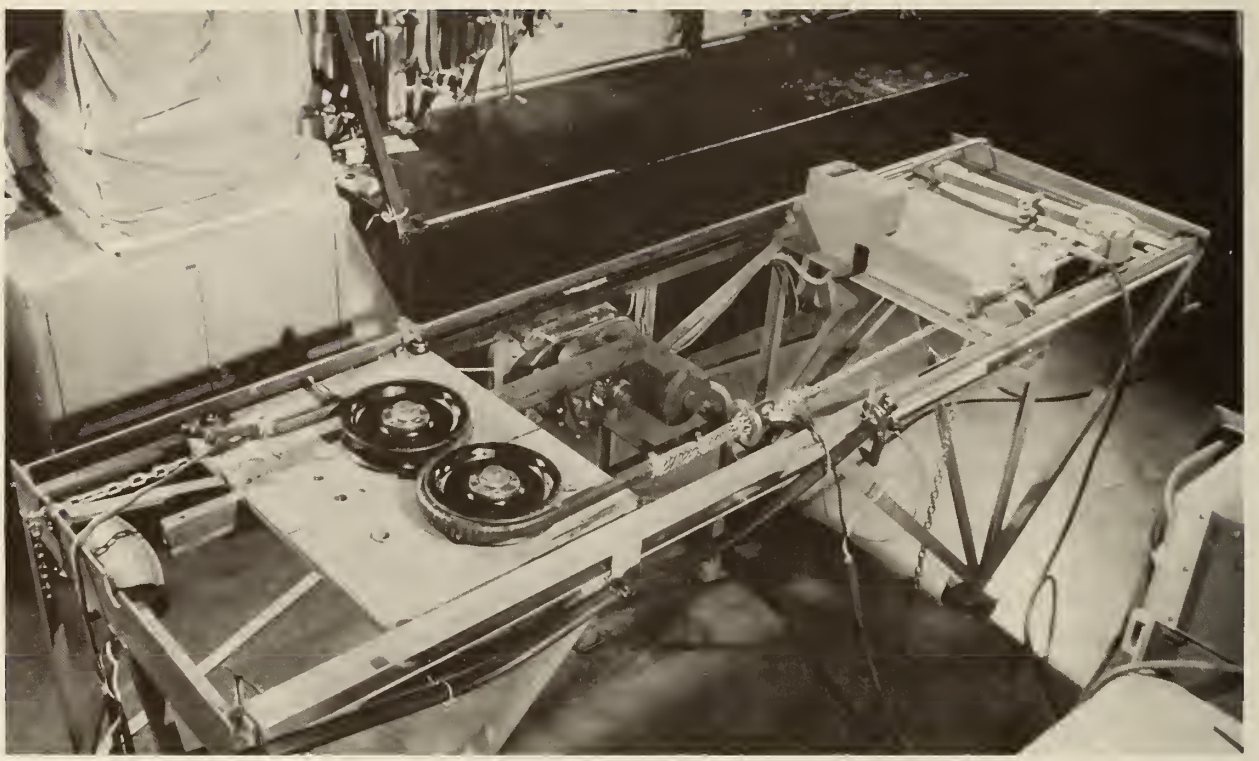

FIGURE 7. - Flexing apparatus (number two type G cable).

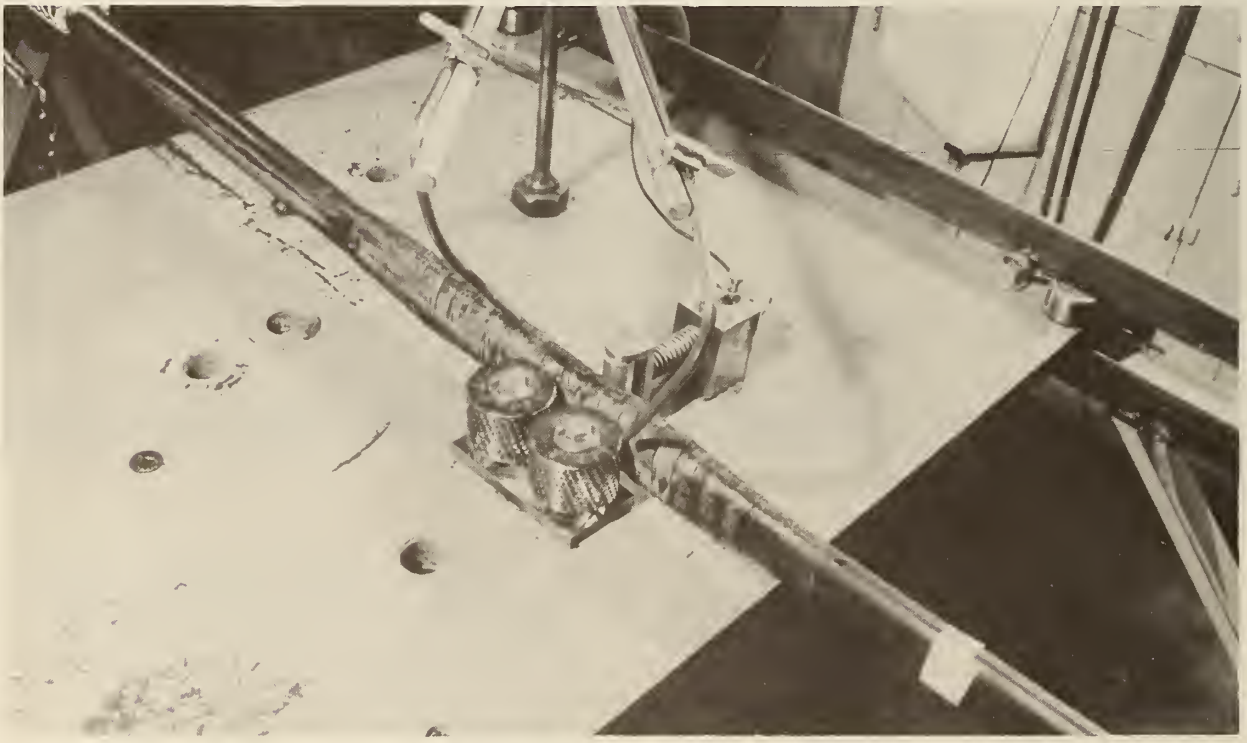

FIGURE 8. - Abrasion apparatus (number two type G cable).

RECOMMENDED TESTING STANDARDS

The current federal regulations (the 1969 Coal Mine Health and Safety Act) requires permanent splices to be "mechanically strong," "effectively sealed so as to exclude moisture," and to have "adequate electrical conductivity," "adequate flexibility," and a "good bond to the outer jacket." Quantitatively defining these restrictions is the purpose of proposing testing standards.

The tests are designed so a splice kit that is easy to apply correctly will have a better chance of qualifying than one that is difficult. Groups of six splices are submitted by the manufacturers for each test. All six must pass each test before they are allowed to use the upset or embossed Bureau of Mines approval number. Since some tests are destructive, a total of 21 splices are required for the four tests:

1. Conductivity.

2. Tension.

3. Flexibility (voltage withstand after flexing).

4. Abrasion.

The conductivity specifications require splice joint resistance to be 1.0 mΩ or less.

Tension specifications (table 3) must be withstood by the total splice. Therefore, the tensile strengths per conductors shown must be summed for a multiconductor cable.

TABLE 3. - Tensile strength required

Conductor size AWG or MCM	Tensile strength required per spliced conductor, pounds	Conductor size AWG or MCM	Tensile strength required per spliced conductor, pounds
14	75	1	1,300
12	100	1/0	2,500
10	150	2/0	3,200
8	250	3/0	4,100
7	325	4/0	5,100
6	400	250	6,000
5	525	300	7,200
4	650	350	8,500
3	800	400	9,400
2	950	500	11,900

The splice shall have to withstand the number of flex cycles indicated in table 4 while bending around the specified diameter sheave wheel and under the specified tensile load. A complete break or open circuit in any conductor defines failure.

TABLE 4. - Allowable flex cycles

Conductor size AWG or MCM	Tension,[1] pounds	Bending, degrees	Flex cycles	Bending[2] diameter, inches
10	150	180	1,500	12 times cable diameter.
8	175	180	1,500	Do.
7	175	180	1,500	Do.
6	175	180	1,500	10.
5	175	180	1,500	10.
4	175	180	1,500	10.
3	175	180	1,500	10.
2	175	180	1,500	10.
1	175	180	1,500	10.
1/0	250	90	200	12 times cable diameter.
2/0	250	90	200	Do.
3/0	250	90	200	Do.
4/0	250	90	200	Do.
250	250	90	50	Do.
300	250	90	50	Do.
350	250	90	50	Do.
400	250	90	50	Do.
500	250	90	50	Do.

[1]Tension is for total cable, not per conductor.
[2]The smaller cable diameter is used when calculating bending diameter of flat cables.

Moisture penetration is measured with the voltage withstand test. After flexing, the splice is submerged in a water bath for 24 hours, and the specified voltage is applied. If current passes between any two conductors or into the water, the splice fails.

Resistance to jacket deterioration from abrasion is determined by assuring that the splice withstands 500 cycles in the abrasion test before any part of a bare conductor, connector, or ground wire is exposed.

TRAINING IMPORTANCE AND CONCLUSIONS

Many of the presently marketed kits contain materials that will result in a safe splice; however, the correct cable preparation and assembly procedure must be used. Proper cable preparation and splicing is not an easy job in the mine environment where coal dust, grease, poor lighting, wet floor, lack of proper tools, and haste are the common way of life.

Therefore, throughout the second year of research, the project investigator worked closely with Casimer P. Zavora (MESA Education and Training Div.) to develop a job safety guide for trailing cable splices. Many coal mining districts were visited to conduct training seminars on proper splicing techniques.

In summary, the research project defines common cable splice failures. These failure definitions outline a test program to point out weak points of splice construction and provide engineering knowledge and results in standards and specifications for the MESA approval process. Furthermore, the knowledge is used in a MESA training program. Recommended kit improvements are communicated to manufacturers.

It is concluded that the two areas of flexibility and moisture penetration need additional research to improve splice performance. Therefore, the Bureau of Mines has initiated two programs to optimize welded and crimped connector design. A third program for optimizing adhesives to improve the bond between the splice jacket and cable is proposed.

CABLE FAULT LOCATING BY ELECTRONIC MEANS

by

George J. Conroy[1]

ABSTRACT

Types and causes of short-circuit and open-circuit faults in mine portable trailing cables are discussed, and techniques for locating these faults are described. Time domain reflectometers (TDR), tone generator, infrared sensing, and high voltage methods are covered. The paper summarizes Bureau of Mines research, including development of a TDR/tone generator sender with auxiliary probe.

INTRODUCTION

Electrical faults in mine trailing cables are usually traceable to one of the following causes, or to a combination of these:

1. Mechanical stresses such as pinching, or scraping of the cable, or sharp and repeated flexing at splices.

2. Stretching of cable until a break occurs, often at a splice.

3. Very high currents that, through excessive heating, embrittle copper and insulation.

4. Arc-over or metallic contact between conductors in splice areas, due to improper splice construction.

The role of high-voltage transients in deteriorating cable insulation has not been assessed, but it is probably a minor cause.

Pinching or metallic contacts in splices usually result in "bolted shorts," short circuits that have very low resistance, unless current flow is sufficient to vaporize one of the conductors and cause an open circuit. If it does not open in this way, chances are that the outer insulation will be breached by expanding gases, so that the location of the fault can often be visually spotted. The bolted short, if not initially visible, could be made so by connecting the cable across a high energy power source and blowing it out, as shown in figure 1. This has been done in underground mines, but it is not recommended. Given the presence of flammable substances, a fire could be started. Since very high currents are used, the rest of the cable is stressed, possibly deteriorating it. Power source components are overstressed.

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FIGURE 1. - Blowing a fault.

FIGURE 2. - Application of high voltage.

There is physical danger to nearby personnel; and in a mine it is not always a simple matter to insure that nowhere along the meandering length of a trailing cable are any nearby personnel.

A fault resulting from cable stretching would usually be an open circuit. These present, of course, very high series resistance that may, however, be

intermittent. Copper slivers resulting from flexure breakage or copper embrittlement, as well as sharp corners on splice sleeves, vagrant strands, aged insulation, and insulation nicks at splices, can result in faults that begin as an arc-over and then, after the ground fault relay has tripped, continue as a carbon track across a gap. These present a relatively high short circuit resistance as long as full line voltage is not applied to the cables, possibly nearly comparable with the normal insulation resistance of the cable, thus making them difficult to locate. A break in the insulation can admit water, again providing a relatively high resistance path.

One way of locating any of these types of fault is to apply a very high voltage between the conductors. Figure 2 shows a James Biddle Co.[2] impulse generator powered by a 40-kV voltage supply. In the impulser, a capacitor is charged until a spark gap breaks down to send a pulse along the cable, after which the cycle repeats. Pulse amplitude is varied by varying the spark gap distance, and pulse repition rate varies with applied voltage. The indication that results may be visual, such as the appearance of smoke from a dry cable or of a stream of bubbles from an immersed cable, or it may be aural, such as the click that occurs at a fault when a high-voltage pulse arcs over at the fault. It may be a glowing spark, which now brings in the problem, with regard to underground mines, of an incendiary hazard. An, of course, hazard to nearby personnel is even more probable with high voltage. An incidental fact is that, if proper grounding procedures are neglected, a cable can remain lethally charged long after the high voltage has been removed. Some cables that have been discharged after application of high voltage can regain part of their charge, bringing them up to perhaps one half of the value of the test voltage. High voltage testing is best restricted to cable repair shops, under the control of thoroughly experienced personnel.

FAULT LOCATION TEST PROGRAM

Three years ago the Federal Bureau of Mines decided to explore means of fault location that would not present serious personnel hazards and that could provide a high probability of success in locating both shorts and opens in visually sound trailing cables. The task was let after competitive request for proposal (RFP) procedure to FMC Corp., in San Jose, Calif., to develop a set of methods that could be used singly or in combination, depending on circumstances, to locate most faults. Prototype apparatus was fabricated and has been extensively used. The principles utilized are the following:

1. Time Domain Reflectometry (TDR).--In this technique, a voltage pulse with fairly steep rise time is sent down cable pairs, and the pulse reflection from any discontinuity is noted. The echo will act to either reinforce or reduce the originating pulse amplitude, depending on whether the discontinuity is an open or a short. The time of arrival of the echo is proportional to the location of the discontinuity, along the length of the cable.

Schematically, the system consists of a timed-pulse source, the faulted cable, and detection circuitry. The pulse leaving the source is steep-fronted.

[2]Reference to specific manufacturers does not imply endorsement by the Bureau of Mines.

The amplitude of the echo may be somewhat diminished over the length of cable; however, the polarity and duration are the important characteristics.

As the echo returns from an open circuit, it adds to the amplitude of the pulse being generated, and this fact tells the detection circuitry that an open is on the cable. The point in time of this added amplitude is measured by the circuit, and this duration is interpreted by the device to yield a digital indication of the distance to the fault.

Where a short-circuit type of fault is on the cable, the returning echo subtracts from the originating pulse.

Extreme accuracy in the TDR method for electronically locating the fault in the cable is not necessarily more useful than is a reasonably good approximation. It is still necessary for the operator to physically locate that portion of the cable from the outside. This requires length measurement such as pacing off the cable, which is itself only an approximation. For this reason, an accessory probe unit is useful for final location, as will be discussed.

An instrument capable of precise fault location was available at the time the FMC contract started, the Hewlett-Packard TDR. This instrument is, however, large and expensive; the instrument utilizes a cathode ray tube and is thus rather delicate; and requires considerable aptitude and skill to operate. The Bureau's TDR, as shown in figure 3, is inexpensive, fairly rugged, battery

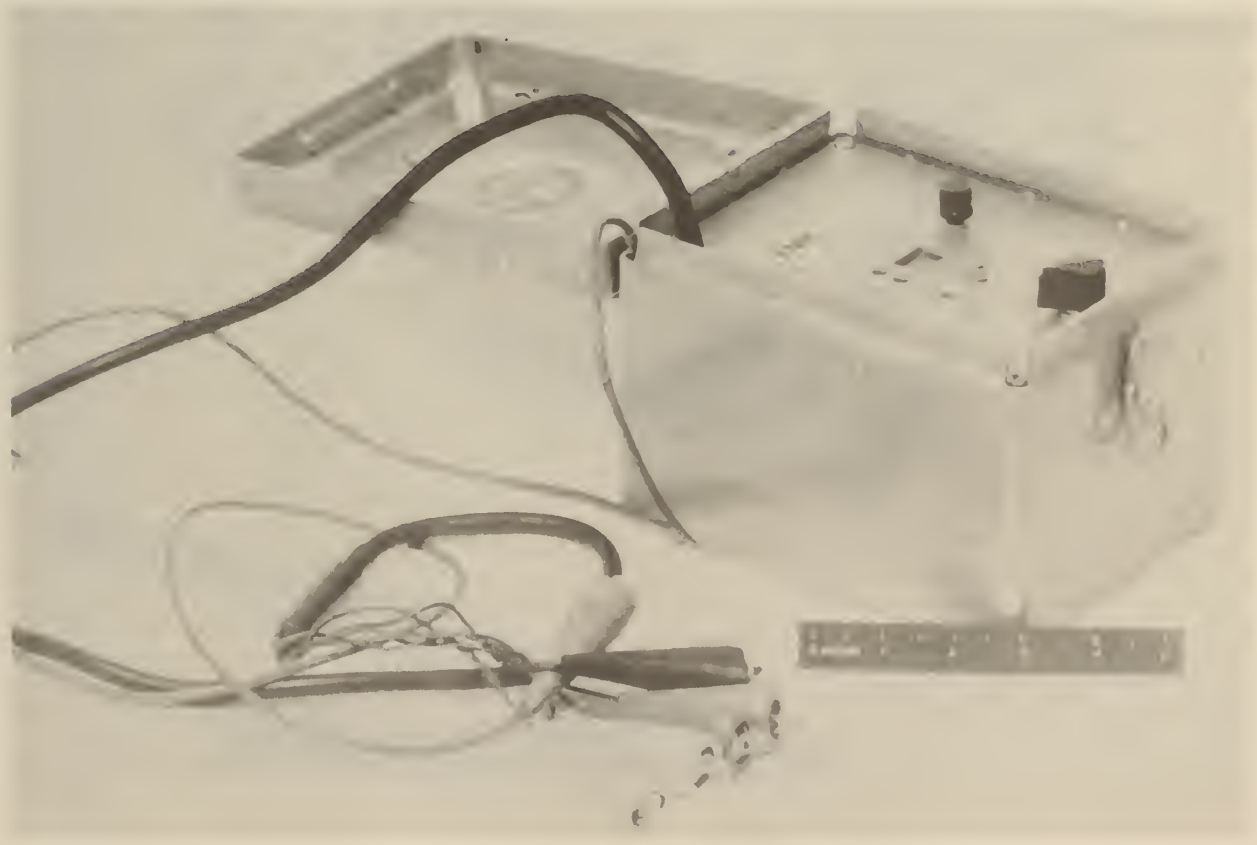

FIGURE 3. - Bureau of Mines time domain reflectometer (TDR).

powered, and provides a digital indication of fault location. Its accuracy is only about ±15 feet, partly because of its pulse characteristics and partly because there is uncertainty about the propagation parameters of various cable insulations. For example, in a 3-phase cable, the red, white, and black insulated conductors have each a different propagation time, so that a somewhat different digital indication occurs for each conductor color. Tektronix now has a TDR, shown in figure 4; this one does not use a cathode ray tube but instead uses a small chart recorder. It has been used for troubleshooting computers. Their newest modification is reported to be suitable for power work. Limited testing on the first model was performed recently to see how adaptable it is to mine use, and the new one will be tested when available.

A problem inherent in the Bureau's apparatus is its inability to locate shorts that have resistance values higher than a few ohms. This is partly the result of a desire to keep the TDR pulse amplitude low, to assure intrinsic safety. The level is approximately 2-1/2 volts. The peak voltage when the apparatus is in the tone generator mode is about 12 volts. Now, in many mine power centers, the ground fault relay could trip at fault currents as low as

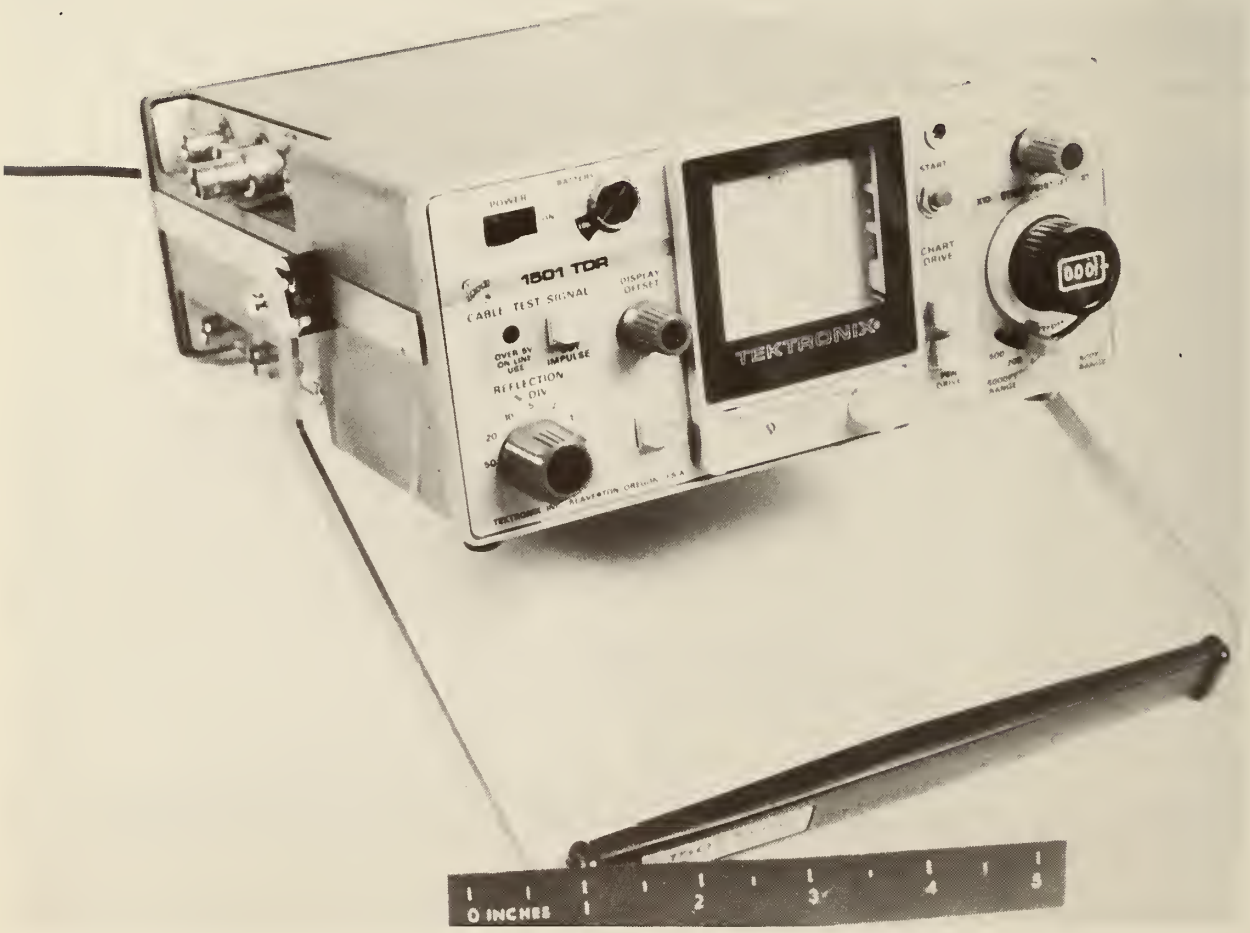

FIGURE 4. - Tektronix TDR.

5 amperes. The fault resistance corresponding to this value would be in the neighborhood of 40 ohms. If the circuit breaker interrupts current flow rapidly, as it should, the energy developed at the short is very limited; for this reason, there is no external evidence on the cable that might help locate the short. Here is the type of fault where an electronic locator could be most useful. Yet the Bureau of Mines TDR device cannot adequately locate such a fault. To improve this situation, the Bureau has at present a contract with Carnegie-Mellon University to modify the present Bureau instrument to provide a higher voltage.

The Bureau's original requirement of intrinsic safety was based on convenience; it avoids the necessity for taking special safety precautions while repairing cable in the working face area. However, as it is now established that pulse voltage must be higher in order to accomplish the task, some precautions such as a methane check may be necessary.

Tests so far indicate that a 40-volt peak, steep-fronted pulse is sufficiently high to locate most important faults. This is a reasonably safe level from the personnel shock standpoint; MESA regulations, for example, permit a maximum of 40 volts to appear from frame to ground during a ground fault. At this voltage it may not be necessary to provide substantially housed connectors at the point of connection to the trailing cable, in order to avoid electrical shock. Simple clips with rubber boots are probably sufficient. If the device used supplies a higher voltage at the terminations, use of an enclosing connector is recommend.

The technique for using the Bureau's apparatus is to approximately locate the fault with the TDR, then switch to a tone transmitter mode, sending an audio frequency signal down the cable. If the fault concerned is a short circuit, as schematically pictured in figure 5, the audio current flowing in the loop: (Sender-cable line 1--short circuit cable line 2--sender) is inductively coupled through a pickup coil to the amplifier of a probe which is moved along the cable. As the short is passed by, the probe coupling ceases as indicated by a meter deflection. If the fault is an open circuit, the impressed voltage is capacitively coupled to the moving probe through a floating electrode, as shown in figure 6; and as the break in the wire is passed, the absence of impressed voltage results in a meter deflection. In practice, the locating by probe of a short or an open is accomplished the same way, as far as the operator is concerned, even though there are two different principles of signal sensing involved.

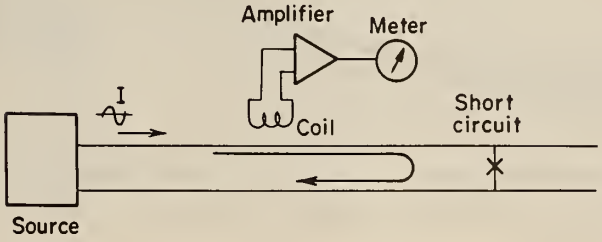

FIGURE 5. - Short-circuit location principles.

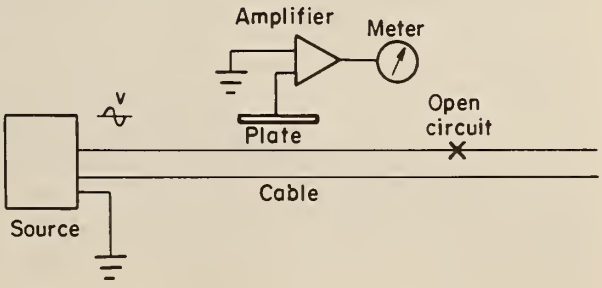

FIGURE 6. - Open-circuit location principles.

So far as the tone generator-plus-probe method of fault location is concerned, we have found that a commercially available "0 to 300 volt" tone generator and a cable route tracer, in combination, can successfully locate both low and high resistance shorts, including salt water seepage. The items we tested were made by James Biddle Co. (figs. 7-8). The generator shown operates from a 12-volt auto battery. The same apparatus can, when used with care, aid in finding open circuits. A system made by Pyott-Boone called the Megatron consists of a source, which is essentially a resistor placed in series with the cable on the 110-V ac line (fig. 9), and a probe, which responds to the cable's magnetic loop current (fig. 10), as previously described. Because the open-circuit voltage is high, this system can also locate high resistance shorts with some degree of success. Of course, with these available systems, one may be forced to traverse the entire length of the cable, as contrasted with the Bureau's system of first approximately locating the fault and then zeroing in by means of the probe. Nevertheless, they are available.

Various tests have been conducted with the Bureau's TDR and probe in cable repair shops and mines. Most tests were successful. Exceptions were once when an internal componenet became defective and once when a fault was simulated by boring the insulation and introducing saltwater. Upon our recommendation, U.S. Steel conducted tests of the apparatus constructed by FMC for the Bureau and of the Biddle units described, at Gary mine and reported success. I believe they have since purchased the Biddle units.

While open circuit voltages must be reasonably high, the total energy dissipated at the fault during the test should be low to avoid incendive effects. The TDR, with its short pulse at a low repetition rate, can be made to fulfill the requirement. The tone generator is incapable of putting out more than a few watts, and in any case, its output can be deliberately limited by means of an added series capacitor. This point should be kept in mind when using any commercially available, elevated voltage signal source. In this regard, remember that a 75-ohm series dropping resistor, or other impedance, does not reduce the open-circuit voltage. If it is 115 volts ahead of R, it is still line voltage at the terminals. Not only incendive effects, but also electric shock hazard are present. Use appropriate precautions.

An alternative to the audio frequency probe is the infrared probe shown in figure 11, used to locate shorts in shielded cables. Current from a source connected to the cable terminals, flowing through the short circuit, raises the local temperature (fig. 12). This temperature rise is sensed by an infrared probe sensitive to about 1 or 2 degrees fahrenheit. The first Bureau prototype utilized an audio frequency current; however, the high power required (35 watts or more) makes a tone generator rather expensive, and the audio frequency is not necessary. A relatively inexpensive multitap transformer current source operating at 60 Hz can be successfully utilized. The system can detect short circuits with resistance up to about 60 ohms. Safety precautions again would be necessary if the equipment is used in the working face area, because of the substantial current (up to 60 amps) involved. Maximum voltage is about 50 volts, at low current.

FIGURE 7. - Biddle tone transmitter.

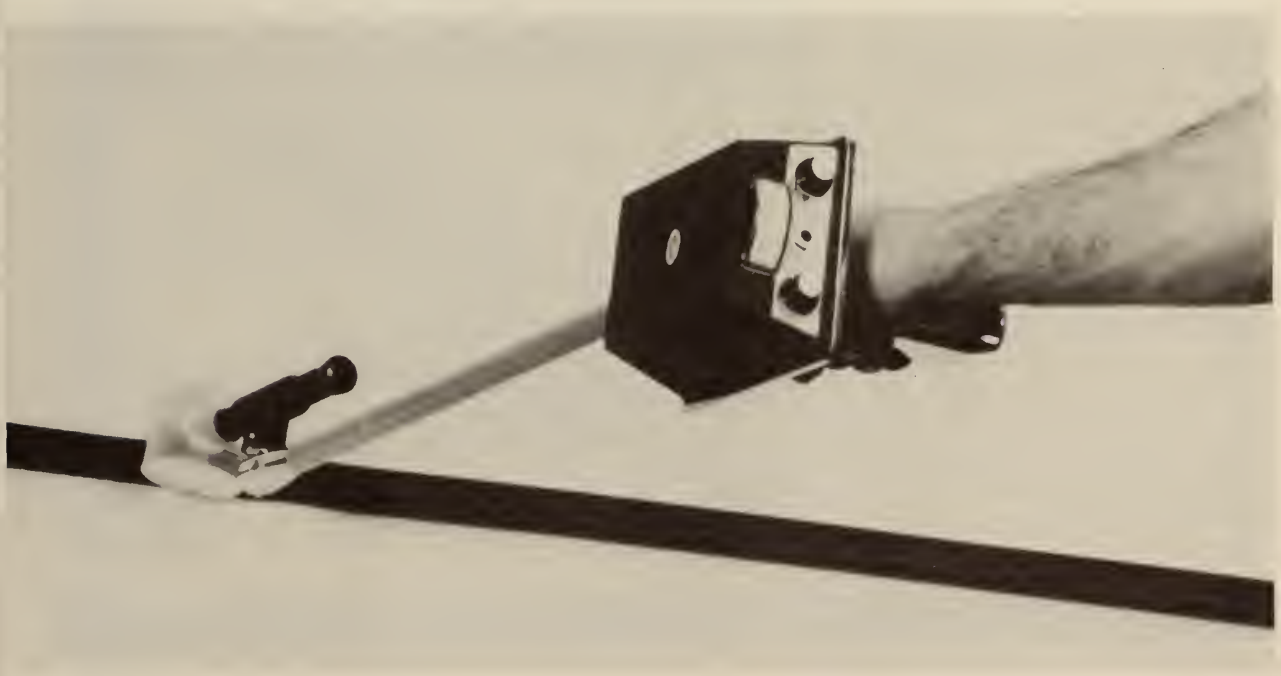

FIGURE 8. - Biddle route tracer.

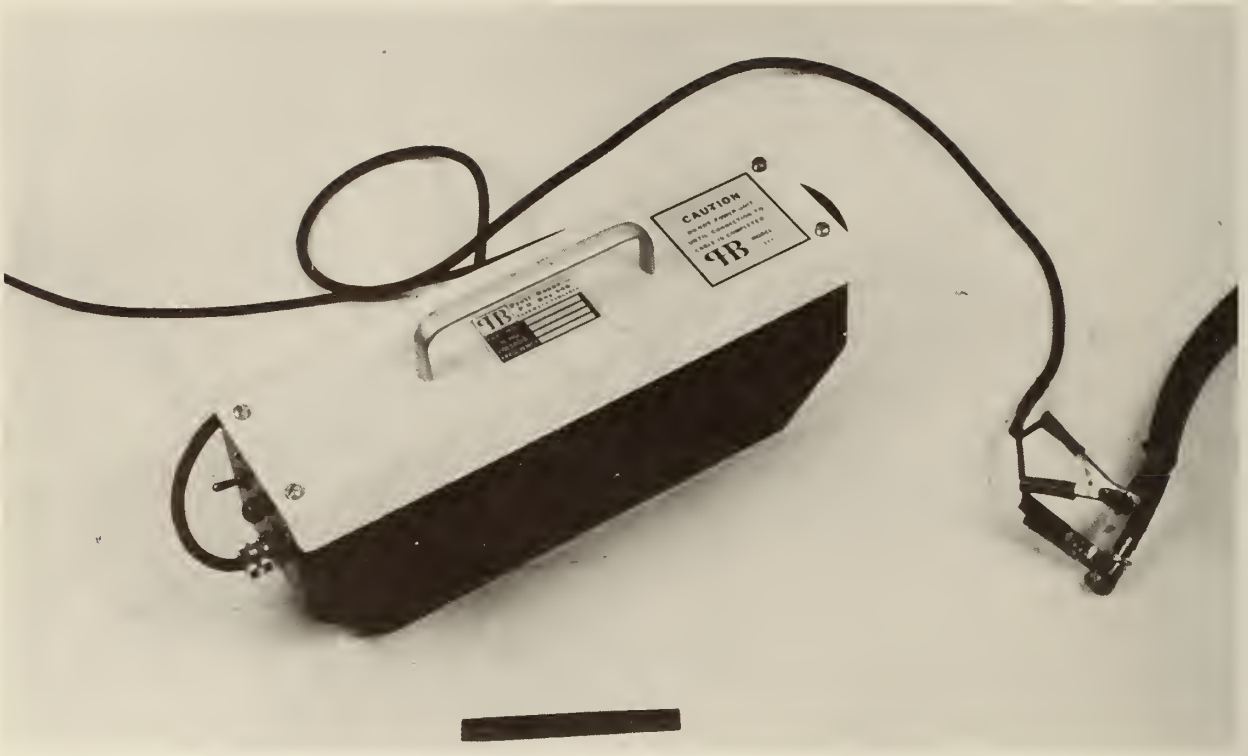

FIGURE 9. - Megatron supply.

FIGURE 10. - Megatron probe.

FIGURE 11. - Infrared probe.

FIGURE 12. - Infrared method survey.

Early tests that successfully located faults through infrared emission utilized a Barnes Engineering Co. probe. This unit is commercially available and is quite sensitive. It is, however, more delicate and not as convenient to use as the Bureau probe.

The infrared unit can be used with both shielded and unshielded cables and in fact, is the only probe type of apparatus capable of consistently locating short circuits in shielded cable. Even it would not locate opens. High voltage click methods or, for that matter, even the direct practice of piercing the cable with needle probes and noting continuity could not be depended on for the purpose because of the shortcircuiting effect of the shield. The TDR, however, functions satisfactorily on shielded as well as unshielded cable.

The TDR, then because of its universality and the fact that walking the cable is reduced, is a very attractive apparatus for fault locating. To be successful in mines, the device should be highly portable, rugged, fairly accurate, and provide an unequivocal fault indication. The latter requirement is met by means of digital display.

The present contract with Carnegie-Mellon, in addition to requiring as an interim device an elevated voltage version of the Bureau's TDR made by FMC, calls for development of a unit that will sample the response of every foot of the cable and indicate successively the precise location of any number of faults. This investigation is just getting started.

SUMMARY

Commercial units suitable in cable repair shops where proper safeguards can be taken include several brands of high-voltage impulse devices. Where ruggedness is not a requirement, TDR units such as the Tektronix unit may be useful. The Bureau TDR-plus-probe combination could be built today by anyone sufficiently motivated and would provide ruggedness and simplicity for use in the underground mine. Also, an elevated voltage tone generator and probe and a 50-Hz system are available today and provide aid within their limitations. The FMC infrared probe can locate short circuits in shielded cable. Incidentally, we have a few of these units which we would be happy to lend out for trial, on a cooperative basis. The higher voltage version of the Bureau's TDR will be field tested in a few months. This TDR will approximately locate opens, high resistance shorts and low resistance shorts, in shielded or unshielded cable, strung out or on a reel. It will probably still require searching over some 30 feet or so of cable with a probe supplied as part of the system. A year or so later, this set will be followed by a TDR that gives precise location of multiple faults in one test. Probe searching should thereby be considerably reduced.

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